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Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments

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ABSTRACT

Published estimates of the potential of bioenergy vary widely, mainly due to the heterogeneity of methodologies, assumptions and datasets employed. These discrepancies are confusing for policy and it is thus important to have scientific clarity on the basis of the assessment outcomes. Such clear insights can enable harmonisation of the different assessments. This review explores current state of the art approaches and methodologies used in bioenergy assessments, and identifies key elements that are critical determinants of bioenergy potentials. We apply the lessons learnt from the review exercise to compare and harmonise a selected set of country based bioenergy potential studies, and provide recommendations for conducting more comprehensive assessments. Depending on scenario assumptions, the harmonised technical biomass potential estimates up to 2030 in the selected countries range from 5.2 to 27.3 EJ in China, 1.1 to 18.8 EJ in India, 2.0 to 10.9 EJ in Indonesia, 1.6 to 7.0 EJ in Mozambique and 9.3 to 23.5 EJ in the US. From the review, we observed that generally, current studies do not cover all the basic (sustainability) elements expected in an ideal bioenergy assessment and there are marked differences in the level of parametric detail and methodological transparency between studies. Land availability and suitability lack spatial detail and especially degraded and marginal lands are poorly evaluated. Competition for water resources is hardly taken into account and biomass yields are based mostly on crude ecological zoning criteria. A few studies take into account improvements in management of agricultural and forestry production systems, but the underlying assumptions are hardly discussed. Competition for biomass resources among the various applications is crudely analysed in most studies and key assumptions such as demographic dynamics, biodiversity protection criteria, etc. are not explicitly discussed. To facilitate more comprehensive bioenergy assessments, we recommend an integrated analytical framework that includes all the key factors, employs high resolution geo-referenced datasets and accounts for potential feedback effects.

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1. Introduction

As global interest and inquiry into the achievable and sustainable potential of bioenergy grows, numerous studies have been conducted to better understand the potential of this renewable energy resource. These existing biomass energy resource assessments are providing widely varying estimates and present different scenarios of the potential contribution of biomass to future energy systems. Dornburg et al. [1] reviewed a range of studies and concluded that the technical bioenergy potential in 2050 could range from about 100 EJ using only residues up to an ultimate technical potential of 1500 EJ/yr when considering all types of feedstocks, and considering maximum deployment of agricultural intensification. Similarly estimates are given in an International Energy Agency (IEA) study [2]. In the IPCC Special Report on Renewable Energy [3] it is concluded that in 2050, the total assessed bioenergy potential can range from below 50 EJ/yr (in scenarios with high future food and fibre demand, combined with lower agricultural productivity) to about 500 EJ/yr technical potential, taking key sustainability criteria (e.g. food, water, biodiversity) into account. A deployment rate of 100–300 EJ is estimated in this report by 2050. Many other studies provide varying intermediate estimates (e.g. Haberl et al. [4] give a more conservative global technical bioenergy potential of 162–267 EJ/yr in 2050 after taking into account strict sustainability criteria. Beringer et al. [5] also conclude that the total global bioenergy potential for the year 2050 ranges between 126 and 216 EJ/yr).

According to Hoogwijk et al. [6], Smeets et al. [7] and Haberl et al. [4] the discrepancies in bioenergy potential estimates are caused by several factors. First, studies have different objectives, scope/system boundaries and are evaluated over different time frames (see also Thrän et al. [8]). Second, studies focus on different biomass resource types (e.g. energy crops, residues, etc.) and different type of biomass potentials (e.g. theoretical, technical, economic, sustainable, implementation). Third, a heterogeneous assortment of methodologies and approaches is used to derive bioenergy potential estimates. More importantly, analysts use a heterogeneity of datasets and scenario assumptions (due to missing empirical data) for certain aspects (e.g. yields, conversion factors, parameter correlations, and sustainability criteria). The broad variety of approaches, methodologies, assumptions and datasets is due to a lack of a commonly accepted approach to determine biomass energy potentials.

These differences in bioenergy resource assessment estimates make it difficult to clearly inform decision-making by policymakers and investors. Utilisation of the available estimates requires harmonisation of the results and understanding their basis, i.e. by examining the authenticity, credibility and accuracy of underlying assumptions, data and correlations as well as methodological completeness. Although most analysts indicate that they take into account generally accepted key factors that influence bioenergy potentials, often these factors are not explicitly discussed in the relevant study reports. This makes comparison and harmonisation of study results difficult. While some studies lack transparency in the procedure for estimating bioenergy potentials, others neglect important sustainability criteria, such as competing biomass applications in their estimates [4,8,7,9]. It is important to note that differences in biomass energy potentials per se are not the problem, but lack of transparency and omission of key factors that influence sustainable bioenergy potential makes harmonisation of results from different studies difficult.

Given the lack of convergence in bioenergy resource assessments and difficulties encountered in attempts to harmonise study results, two issues emerge. First, to enable harmonisation of current bioenergy study results, there is a need to develop a systematic approach to evaluating and qualifying current assessments by determining what factors have been included and excluded, as well as examining if key parameters employed in the analysis are within 'reasonable' deviation of commonly accepted values. Second, there is a need to provide an analytical framework to guide future bioenergy assessments so as to ensure that the critical factors influencing biomass availability as well as sustainability issues are taken into account.

The main objective of this paper is to review and analyse methodologies and approaches used in estimating bioenergy potentials, focussing on identifying the critical elements that influence the results as well as gaps in knowledge and understanding in aspects that have a strong impact on the outcome of bioenergy potential assessments. From the analysis, we develop and present a systematic methodological framework for conducting comprehensive bioenergy resource assessments (for both regional/national and global level). This methodological framework can also be useful as a quality assurance screening tool when applied to reviewing and evaluating existing bioenergy studies. To illustrate this, the methodological framework is applied to a review exercise of several national bioenergy resource assessment studies in five selected countries i.e. China, India, Indonesia, Mozambique and the United States of America (US).

This paper is structured as follows. Section 2 presents a review of current methodologies and approaches used in performing bioenergy potential estimates. Included in this section is an analysis of the critical determinants of bioenergy potentials. This is followed in Section 3 by an analysis of lessons learnt from reviewing and harmonising several national studies. The last section outlines the proposed methodological framework.

2. Evaluation of approaches and methodologies used in bioenergy potential assessments

To enable a systematic evaluation of bioenergy resource assessments, three key aspects taken from the literature are used to categorise and analyse the studies: the type of bioenergy potential, type of approach and type of methodology (following Berndes et al. [10]; Perlack et al. [11]; Smeets and Faaij [12]; Smeets et al. [13]; van Vuuren et al. [14]; Dornburg et al. [1]; Chum et al. [3]). An approach represents a broad guiding philosophy followed in an assessment and is not procedural. Examples of approaches include resource focussed, demand driven and integrated assessments. A methodology on the other hand is a set of detailed procedures that translates correlative assumptions (and datasets) into (quantified) bioenergy potentials. There is a hierarchical and logical fit between an approach and methodology, as the methodology should be based on and be consistent with a particular approach. Examples of methodologies include (resource focussed) statistical analysis and (demand driven) cost supply analysis.

2.1. Type of bioenergy potentials

The type of biomass energy potential is a crucial criterion, because this determines to a large extent the approach and methodology employed in a study and thereby also the data requirements as summarised below.

Three types of bioenergy potentials can be distinguished (following Chum et al. [3]; Smeets and Faaij [12]).

(i) *Theoretical potential*: is defined as the maximum amount of terrestrial biomass which can be considered theoretically available for bioenergy production within fundamental bio-physical limits. In the case of biomass from crops and forests, this represents the maximum productivity under theoretically optimal management of agriculture and forestry, taking

into account limitations that result from temperature, solar radiation and rainfall (see e.g. Sørensen [15]; Kheshgi et al. [16]; Cannell [17]). For residues and waste, the theoretical biomass potentials are the same as the total residue production (see e.g. Edwards et al. [18]; Geletukha et al. [19]).

(ii) *Technical potential*: is defined as the fraction of the theoretical potential which is available under current technological possibilities, and taking into account spatial restrictions due to competition with other land uses (food, feed and fibre production) as well as other non-technical constraints (see e.g. Perlack et al. [11]; Ericsson and Nilsson [20]; Hagstrom [21]; Thrän et al. [22]; Renew [23]). When restrictions related to environmental criteria such as nature conservation and soil/water/biodiversity preservation are considered then this fraction of technical potential is referred to as the *ecologically sustainable potential* (see e.g. EEA [24–26]).

(iii) *Market* (*or Economic*) *potential*: refers to the share of the technical potential which meets economic criteria within given conditions (e.g. competition with fossil fuels or assumed carbon prices). This depends on both the cost of production and the price of the biomass feedstock (e.g. Richards and Stokes [27]; Hagstrom [21]; De Wit and Faaij [28]; Renew [29]). A variant of the economic potential that can be implemented within a certain time frame and under concrete socio-political framework conditions, including economic, institutional and social constraints and policy incentives is referred to as the i*mplementation potential* (e.g. Van Vuuren et al. [30]).

As shown in Fig. 1, there is hierarchical reduction in potential from theoretical to implementation potential and an overlap between market potential and ecological potential. This overlap comes about, for example when biomass potential considered to be ecologically sustainable does not meet economic criteria and vice versa.

It should be noted that the definitions of potentials in literature are often not fully consistent with the definitions presented above. Bioenergy assessments that focus on a certain type of potential often also include limitations that, according to the definitions above, are relevant for another type of potential. Further, several studies explicitly, or implicitly, analyse several types of potentials. For example, the following types of combinations can be identified, i.e. *theoretical–technical* and *economic-implementation* potential.

2.2. Biomass resource categories

Biomass resources include organic materials derived from agricultural crops, forest products, aquatic plants, residues, manures and wastes [6,4]. There are two main biomass resource types which are potential bioenergy feedstocks: biomass from forestry and agriculture. According to Hoogwijk et al. [6], the biomass resource base can be categorised into four interlinked levels: i.e. primary resources, primary residues, secondary residues and tertiary residues resources. Corresponding classification by FAO [31] is direct

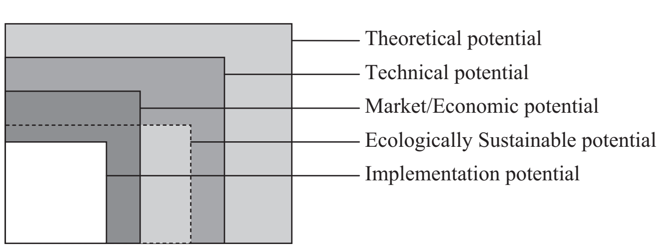


Fig. 1. Overlap between theoretical, technical, and market bioenergy potentials.

(energy crops and by-products), indirect (by-products) and recovered (end-use material) as described in Table 1.

2.3. Types of approaches

The general approach determines to a large extend the methodology that is used and in turn, the methodology determines to a large extend the data requirements. Most biomass energy assessments can be categorised as demand-driven or resource-focussed assessments, see Fig. 2. In addition, integrated assessments, impact/feasibility assessments and review assessments can also be identified.

Resource-focused assessments investigate the total bioenergy resource base taking into account competition between different uses of the resources (supply side) and the biophysiological and environmental limitations of biomass production. These types of studies typically focuses on assessing technical potentials and key parameters examined include the efficiency of food and fibre production, particularly with respect to the availability of water and land resources. Examples of resource focussed studies include Thrän et al. [22] and Smeets et al. [13].

Demand-driven assessments analyse the competitiveness of biomass-based energy systems, or estimate the amount of biomass required to meet exogenous targets such as energy security or renewable energy quotas. These studies typically focus on the economic potential. Typical examples include Perlack et al. [11], USDoE [32] and IEA [33]. Perry [34] classifies demand driven assessments into rule based studies and competition embracing assessments. In rule based studies, allocation of biomass between energy markets and other applications is determined by rules or assumptions that are based on set sustainability criteria. Examples include Hansson et al. [35], Leemans et al. [36], Siemons et al. [37], and Londo et al. [38]. In competition embracing studies, biomass is characterised as a tradable commodity which is forced to compete on the energy and/or agricultural markets. Allocation of resources is not based on ex ante (sustainability) rules alone and such studies deploy optimisation procedures that permit biomass to compete at the margin with other sectors. Examples include CARB [39], Sastri et al. [40], Edmonds et al. [41], FAO and OECD [42], Hansson and Berndes [43], IEA [33], and USEPA [44].

Integrated assessments combine both the demand-driven and resource-focussed approaches. These studies use integrated assessment models (IAMs) designed to assess policy questions, mostly by means of scenario analysis. Examples of IAMs include the Joint Global Change Research Institute's MiniCAM model used by Wise et al. [45]; and the Integrated Assessment Model to Assess the Global Environment (IMAGE) used by Hoogwijk et al. [46] and Van Vuuren et al. [30]. Further discussion of IAMs is given in Section 2.4.5.

Impact and feasibility assessments investigate the technical, economic or environmental feasibility of bioenergy policy targets or the impact of bioenergy policies on certain aspects, such as water scarcity, food security, biodiversity, climate change and employment. Examples in this category include USDoE [32], which investigates the feasibility of replacing 30% of the gasoline consumption in the US in 2030 by biofuels. Fischer et al. [47] evaluate the social, environmental and economic implications of biofuels developments on transport fuel security, climate change, agricultural prices, food security and land use change. Smeets and Faaij [48] assess the impact of sustainability criteria on the costs and potentials of bioenergy production in Ukraine and Brazil.

A fifth and somewhat separate approach is the *review* (*or synthesis*) *approach*, whereby new insights are generated based on existing studies. Review assessments summarise and compare different study results and investigate the underlying factors that determine the future production and use of bioenergy. Examples

Table 1
Categorisation of biomass resources.
Source: [12,3,11,31].

Resource type	Category	Source[a]	Description
Agricultural (*Woody biomass, herbaceous plants, fruits and seeds, others*[b])	Primary/direct[a]	Energy crops	The bulk of primary agricultural biomass resources are expected to come from dedicated energy crops on surplus agricultural land and on marginal/degraded land that is considered unsuitable for conventional agriculture but suitable for energy crops. Energy crops include all crops grown with the purpose of producing biomass for energy use. These can be categorised into second generation energy crops (e.g. perennial grasses and woody crops such as short rotation coppice (SRC)) and first generation energy crops (e.g. grains, sugar and oil crops).
		By-products	Direct agricultural residues are the by-products of agricultural practice and include crop residues from harvesting major conventional annual crops (e.g. corn stover, straw) as well as animal manures and animal byproducts.
	Secondary/indirect[a]		Indirect agricultural residues include residues from processing of agricultural products (e.g. rice husks) and slaughterhouse by-products
	Tertiary/recovered[a]	End-use materials	The tertiary agricultural resource includes municipal by-products e.g. municipal solid waste/ organic waste including household and industrial waste and bio sludge[c].
Forestry (*Woody biomass*)	Primary/direct	Natural and plantation forests	Primary forestry biomass resources include woody biomass harvested from natural forests, plantations and other wooded areas (e.g. orchards, vineyards). Fuelwood extracted from forestlands and excess biomass removed from forestlands (so-called "fuel treatments" to reduce fire hazards) constitute other important biomass resources (see Perlack et al. [11]). Also 'surplus forest' growth in natural forests that is not required for fibre production is another resource (see Smeets and Faaij [12]; Chum et al. [3]).
		By-products	Direct forestry residues include logging residues from conventional harvest operations, thinning and other forest management by-products and land clearing operations (e.g. twigs, branches).
	Secondary/indirect		Secondary forestry resources include primary wood processing industry residues (e.g. sawdust, bark), secondary wood processing mill residues (e.g. trimmings, offcuts) and pulping liquors (black liquor[d]).
	Tertiary/recovered	End-use materials	Tertiary forestry resources include urban wood residues e.g. construction and demolition debris, tree trimmings, packaging wastes and consumer durables.

[a] An alternative classification used by FAO in its Unified Bioenergy Terminology (UBET) is also included here for comparison.
[b] Others include animal by-products, agro-industrial byproducts, end-use material and mixtures of these.
[c] Whereas the waste potential is expressed in terms of its physical and energetic amount before conversion, biogas from sewage treatment plants and landfill gas are derived energy carriers from organic waste and are expressed in terms of their volumetric or energetic amounts.
[d] Black liquor is a waste product of paper making (kraft pulping) and contains unutilized wood fibre, lignin, and other chemicals. With wood as input, 50% wood is converted into fibre and the remaining residues are black liquor.

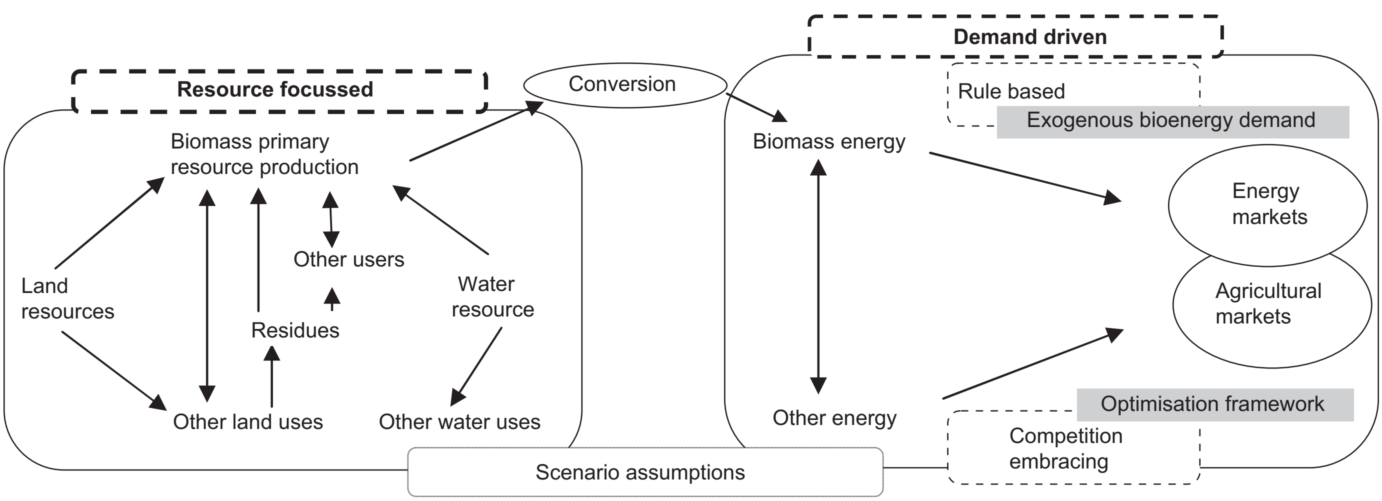


Fig. 2. Representation of 'resource-focussed' and 'demand-driven' approaches.
Source: Following Berndes et al. [10] and Perry [31].

include Berndes et al. [10], Dornburg et al. [1], Thrän et al. [8], Bauen et al. [2], Haberl et al. [4] and Beringer et al. [5] and Offermann et al. [49].

2.4. Types of methodologies

For each approach different methodologies can be distinguished. These methodologies range from simple statistical methods to more complex spatially explicit models and integrated assessment modelling frameworks (that include economic equilibrium models).

2.4.1. Resource-focussed assessments—Statistical analysis

Statistical analysis of bioenergy potentials follow a bottom-up engineering approach to determine the availability of biomass for the production of energy taking into account the demand for biomass for other purposes, such as food and fibre. Important data sets used range from agriculture and forest production, trade to socio-economic developments and technological trends. This methodology is referred to as statistical analysis, because of the use of statistical data on land use and agricultural production. This methodology has been widely used since the emergence of the first biomass potential assessments (e.g. Hall et al. [50,51];

Swisher and Wilson [52]; WEC [53]; Kim and Dale [54]; Karjalainen et al. [55]; Ericsson and Nilsson [20]; Moreira [56]; Smeets et al. [13]; Asikainen et al. [57]).

Statistical data contains empirically derived or modelled statistics of key determinants of biomass resource availability and use. These include information on arable land, cultivated areas, pasture areas, agricultural productivity data, agricultural management systems, harvested volumes, food and material supply and demand elasticities, demographic and economic dynamics, livestock statistics, etc. The most critical data sets include agricultural productivity and animal feed conversion efficiency, key drivers of land use change such as demographics, consumption patterns, income and technological change. Examples of statistical datasets used in bioenergy potential analysis include the FAOSTAT database used in Smeets et al. [13] and Hoogwijk et al. [46], and EUROSTAT database employed by EEA [26] and Fischer et al. [65].

Advantages of statistical analyses are the simplicity, transparency, reproducibility and low cost. A major disadvantage is that it is not possible to adequately account for the macro-economic dimension, which is especially important when evaluating the feasibility of an increase in food production efficiency and thus also the availability of land for energy crop production. Another disadvantage is the limited possibilities to account for site specific environmental or social constraints, as only average values such as soil productivity can be included (as in Renew [23]).

2.4.2. Resource-focussed assessments—Spatially explicit analysis

Spatially explicit analyses differ from statistical analyses because they employ spatially explicit data. However, the key scenario variables remain the same as in statistical analyses. Examples of spatially explicit analyses include Van Dam et al. [58], De Wit and Faaij [28], Fischer et al. [59], van der Hilst et al. [60], Beringer et al. [5], Lotze-Campen et al. [61] and Acosta-Michlik et al. [62].

Spatially explicit analyses are more suitable, compared to statistical analyses, to reflect the impact of local or regional circumstances by combining spatially explicit data on land use. Further, spatially explicit analyses also give insight in the distribution of the biomass potentials across countries or regions. Another advantage is that the yields of energy crops can be estimated based on crop growth models that use spatially explicit data on climate, soil type and crop management. In addition, the methodology is transparent and varying levels of data details and aggregation can be employed [63]. Reproduction of the results is, however, difficult, because the use of geographic information software and spatially explicit data can be labour intensive. Also, the increased complexity of the aggregated data can be a source of uncertainty and contradictions [60], and thus spatially explicit analyses do not necessarily provide more accurate outcomes compared to statistical analyses. Further, spatially explicit analyses, as statistical analyses, offer only limited possibility to include feedback mechanisms such as macro-economic impacts of increased bioenergy production.

The data sets used in spatially explicit assessments can be classified into geodata and statistical data. Geodata is a collection of all georeferenced information such as land use and land cover maps and data obtained from geographic information systems (GIS). This includes datasets on elevation, agricultural suitability, protected areas, population and livestock density, distance to forests and water. A typical example of datasets required in spatially explicit analysis for evaluation of the availability of land for different scenarios is shown in Fig. 3. Examples of geo-datasets include the Global Land Cover 2000 (GLC2000) land cover/use datasets used in Ten Brink et al. [64] and the CORINE Landcover 2000 datasets employed in EEA [26].

An example of a global spatially explicit bioenergy potential assessment is given in Lotze-Campen et al. [61] in which spatially explicit analysis of land-use and water-use patterns are combined with socio-economic information on population, income, food demand and production costs. Spatially explicit environmental data on potential crop yields and water availability for each grid cell are supplied by the Lund–Potsdam–Jena dynamic global vegetation model with managed Lands (LPJmL) while the economic–environmental integration is provided by the model MAgPIE.

2.4.3. Demand driven assessments—Cost–supply analysis

Cost–supply analyses typically combine bottom up bioenergy technical estimates with cost accounting evaluation of the costs of biomass production, transportation and conversion. The results are normally expressed as cost–supply curves. Examples are Parker et al. [66], IEA [33], EEA [24,25], and Gordon et al. [67,68].

This methodology is simple, transparent, reproducible and cheap. However, it does not allow the matching of demand and supply through prices, and thus competition is not accurately modelled. Another disadvantage is that there are limited possibilities to account for environmental or social limitations. Notable exceptions include Smeets et al. [69,48], van der Hilst et al. [70], and van Dam et al. [71], in which the impacts of environmental and social sustainability criteria on bioenergy cost–supply curves are demonstrated.

2.4.4. Demand driven assessments—Energy-system modelling

Energy–economics models, or energy–system models, are models that mimic energy markets dynamics, and evaluate the sufficiency and competitiveness of (bio)energy options through application of economic (least cost) optimisation taking into account changes in production factors, market prices and other economic developments (e.g. technological changes and improvements in agricultural management). Examples of studies employing energy systems modelling include Berndes and Hansson [72], IEA [73,74], Link et al. [75] and OECD [76]. These types of models are especially suitable to evaluate the costs and effectiveness of policy options.

According to Dornburg et al. [77], the ideal energy–economics model takes into account all key factors influencing energy demand and includes all relevant energy supply options, sectors and competing applications. In addition, the model must employ least-cost supply rules and dynamic cost–supply curves that take into account technological learning. For agricultural and forestry–economics models the same criteria apply and in addition, the effects on markets and production of all relevant supply and demand sectors (food, feed, fuel and materials) need to be taken into account.

Dornburg et al. [77] reviewed several energy–system models (including the World Energy Model (WEM)—see [74], Targets-Image Energy Regional model (Timer) and the Market Allocation (Markal) model). They observed that in most studies, potential applications of biomass feedstocks are hardly elaborated, biomass costs are assumed constant while it is unclear how technological learning is included in many studies. A general drawback with energy system modelling is that economic correlations used in the models are partially based on expert judgement, to complement historical data on energy use and prices (which are often distorted by, for instance, changes in energy policies) [78]. Further, energy–economic models lack physical reality, especially validation of land availability and productivity for energy crop production [61].

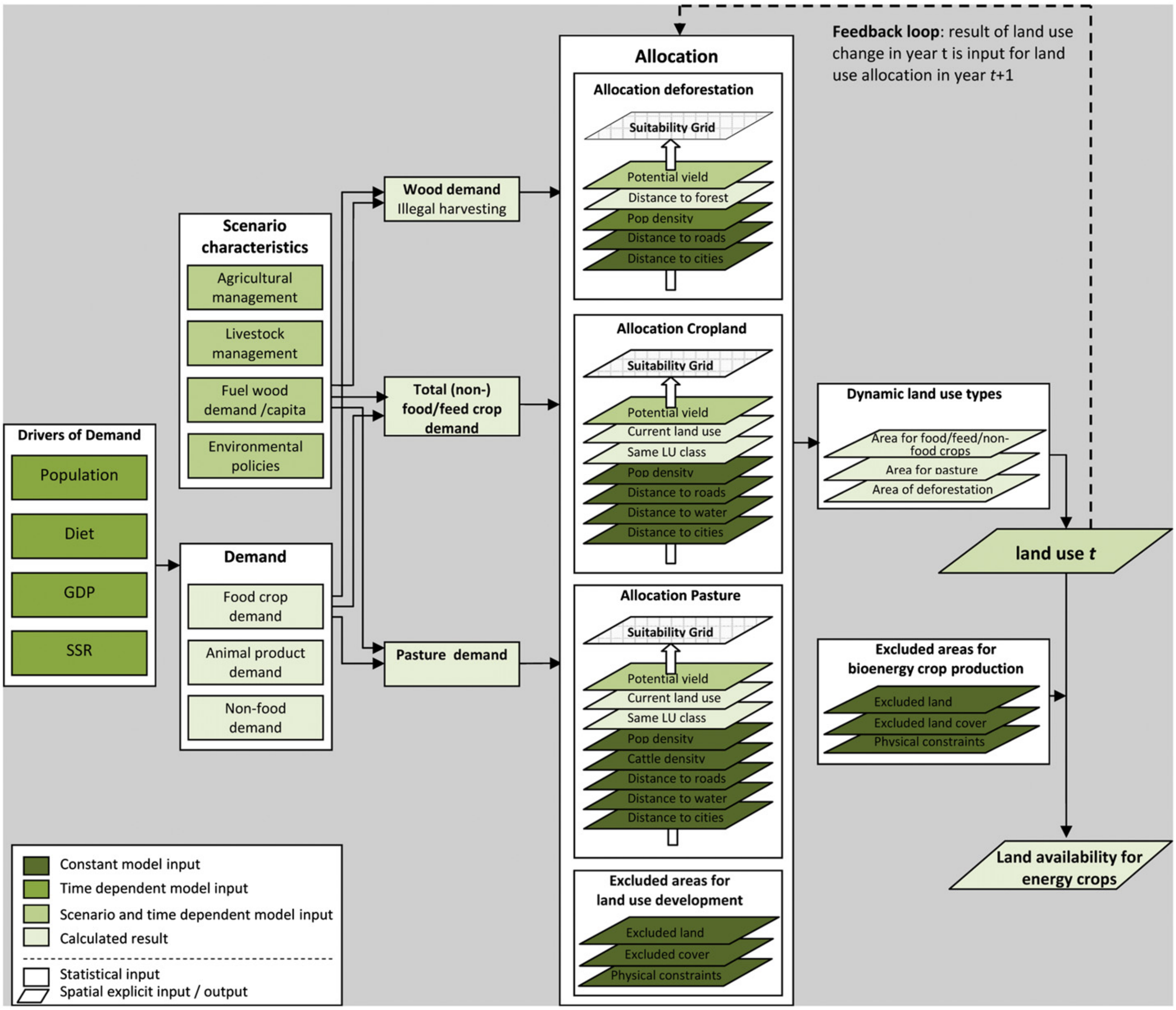


Fig. 3. An overview of modelling land availability for bioenergy crops in a typical spatially explicit analysis.
Source: van der Hilst et al. [57].

2.4.5. *Integrated assessments—Various methodologies*

Integrated assessments (IAMs) combine the resource focussed and demand driven methodologies discussed above. Some IAMs consist of several linked models and tools. IAMs include correlations between socio-economic drivers of economic activity and energy use, which result in environment impacts and feedbacks that lead to changes in the socio-economic drivers. In addition, IAMs combine information about economic, energy and climate variables across various scientific disciplines, time, and spatial scales while allowing the modelling of multi-dimensional scenarios, whereby a large variety of assumptions for different parameters (population growth, economic growth, food consumption, environmental policies, trade, etc.) can be consistently correlated. Several studies use the storylines approach of the IPCC Special Report on Emission Scenarios (SRES) [79]. These scenarios are applied in Hoogwijk et al. [46,80]. These storylines follow specific development trends that make certain assumptions about future socio-economic, technological and environmental development (see Fig. 4).

In theory, IAMs would be ideal for including different sustainability aspects of bioenergy production, including all relevant feedback mechanisms such as macro-economic impacts as well as trade-offs and synergies among the social, economic and environmental dimensions (such as balancing land use choices for food and fuel production, use of by-products and co-production of food, feed and fuels). Because IAMs combine bottom up data on land use and productivities with energy–economic models, they therefore provide an appropriate framework to also estimate the impacts on agricultural markets and food security, GHG emissions and land use. An important handicap is the complexity of these models, which makes them relatively untransparent, expensive to develop and user unfriendly. Moreover, the integration of separate models, and the uncertainties due to gaps in knowledge and data are often problematic in IAMs.

Ten Brink et al. [64] is an example of a study that uses an integrated economic–biophysical framework to assess the impacts of biofuels on biodiversity, climate change and land use change. It combines the agricultural trade model (the extended

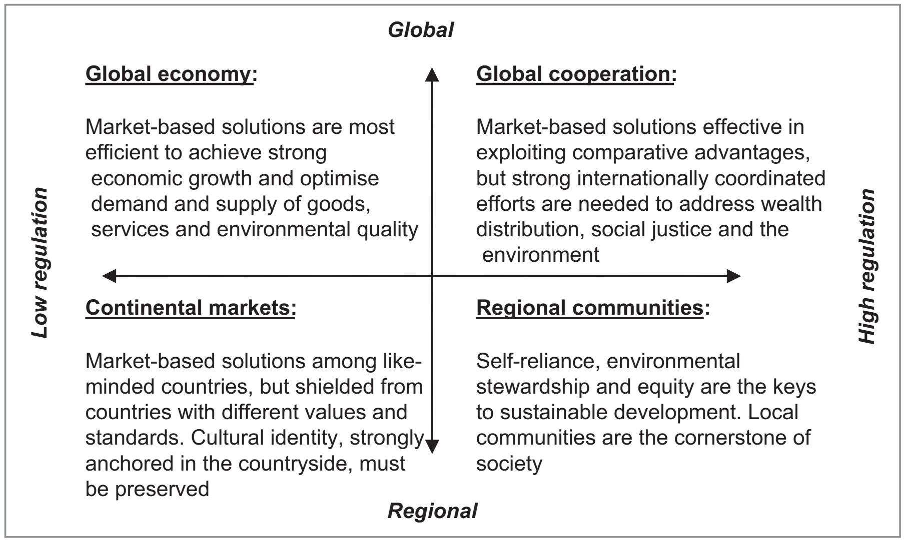


Fig. 4. An example of the story lines approach.
Source: Eickhout and Prins [78].

GTAP: Global Trade Analysis Project), the global integrated environmental assessment model (IMAGE: Integrated Model to Assess the Global Environment) and the global biodiversity assessment model (GLOBIO3). The outputs of GTAP–IMAGE are fed to the biodiversity model GLOBIO3 and the environmental impacts of biofuels that include land use change, agricultural and energy markets can be observed. This typically cannot be derived from single aspect studies. Also, Van Vuuren et al. [14] use the IMAGE–TIMER modelling framework to evaluate the impact of land degradation, water scarcity and biodiversity protection on bioenergy potentials. The study overlays bioenergy potential maps created in IMAGE with maps of land degradation (using the GLASOD soil degradation database), water scarcity (calculated by the WaterGap model) and potential expansion of protected areas (estimated using the Sustainability First scenario of the Global Environmental Outlook of UNEP).

2.5. Key drivers and factors affecting bioenergy potential estimates

For each approach/methodology and bioresource type, biomass availability for energy is influenced by several key underlying factors and drivers. For energy crops, land availability and crop yields are key determinants of bioenergy potential. Sustainability criteria represent important constraints for bioenergy potential estimates (including residues), and variations and omissions in applied criteria (both the type of criteria and the incorporated threshold values) are a major source of discrepancies in available estimates. An ideal comprehensive bioenergy resource assessment would consider all important factors that influence the sustainable availability of biomass for energy, including reduction factors to avoid socio-economic and environmental impacts. An overview of the linkages between the various factors affecting biomass energy potentials and key modelling parameters is shown in Table 2 (partly based on Dornburg et al. [1]).

2.5.1. Biomass demand for food and materials

Several resource-focussed studies use existing projections of per capita food intake and population growth as input data (e.g. Berndes and Hansson [72]; Van Dam et al. [58]; Fischer et al. [65]; Berndes et al. [81]; De Wit and Faaij [28]; Dornburg et al. [77,82]), where for example FAO or EUROSTAT projections are included. These projections are considered as state-of-the-art, although also these projections obviously have their limitations.

Long-term population projections have proven difficult to determine [83] and the uncertainties can have a significant impact on the availability of land for energy crop production. Experiences with population projections from the 1960s have not been accurate showing that population dynamics tend to change significantly over time. An evaluation of past population projections from the UNPD revealed that global aggregated projections had a projection error between +0.5 and +7% [84]. This uncertainty is partially incorporated in studies that use the IPCC SRES scenarios, whereby for each scenario, different population growth projections are assumed.

Similarly, projections of global food production and consumption contain substantial uncertainty and vary much more than population projections, especially for developing countries. At the regional level, food consumption and production forecast errors in the range of ±10 to 40% are common, indicating the effects of domestic policies. Döös and Shaw [85] and IFPRI [86] provide insights into the accuracy and reliability of food security. They conclude that projections published by the IFPRI, USDA and FAO are the most reliable. Various bioenergy assessments (e.g. Johansson and Azar [87]; Lapola et al. [88]; Wirsenius et al. [89]; Beringer et al. [5]) account for the uncertainties via scenario analysis by modelling land availability as a function of domestic policies.

2.5.2. Land availability

According to Berndes et al. [10], Marland and Obersteiner [90] and Chum et al. [3] discrepancies in bioenergy potentials from energy crops are mainly a result of differences in the two most crucial parameters, land availability (and quality) as well as biomass yield assumptions. These two parameters are subject to widely different judgements. It is therefore critical to understand the factors that constrain availability of land as well as achievable yields (see Section 2.5.3 for a further discussion on yields).

2.5.2.1. Categorisation of suitable land resources. Various types of land resources have been identified as suitable for growing energy crops. Two main categories are commonly considered: excess agricultural (arable) land and areas that are considered constrained or not suited for traditional agricultural purposes (due to limiting conditions with respect to topography, climate,

Table 2
Critical factors in biomass energy potential assessment.

Drivers and factors	Main requirements/inputs/aspects to be included for comprehensive potential assessments
Biomass demand for food, feed, and fibre/biomaterials	• Accurate projections of socio-economic trends e.g. population, economic growth, changes in diet and per capita caloric food intake that determine absolute food demand and diet composition (especially meat products); • demand for agricultural land for food, feed and fibre production and other land appropriated for human activities, and surplus land availability for energy crops; • impact of alternative protein chains (this has potential to release land used for feed crop production); • analysis of trade possibilities (optimised global agricultural commodity production can allow best suited regions to produce either food or energy without affecting food security).
Improvements in agricultural and forestry management and technologies	• Assessment of impact of improved agricultural and forestry management efficiency and productivity (and related food production land needs); • accurate mapping of energy crop yields; • potential improvements in animal feed efficiency (and alternative feeds); • intercropping possibilities, integrated agroforestry and silvopastoral systems; • impact of improved harvesting technologies; • impact of biotechnological improvements and technological learning in agricultural production and technology; • impact of multi-product and integrated biorefinering.
Use of marginal and degraded land	• Accurate and spatially explicit land-use datasets and digital mapping identifying location, extend, severity and availability of degraded/marginal land for energy crops; • data on soil quality, conditions and constraints (nutrient retention and availability/fertility, rooting conditions of plants, flooding, soil depth, groundwater depth); • accurate energy crop productivities by type on degraded land; • data on reference land use system of degraded land including use for grazing; • data on biodiversity values of degraded land.
Water availability and use	• Good quality water availability statistics (current and future) including mapping of water stress, ground and surface water availability and quality, environmental water requirements, agricultural water withdrawal, freshwater runoff, freshwater demand by application; • projected climate change impacts (precipitation and evapotranspiration rates); • impact of improved water use efficiency; • impact of energy crop choices and agro-management (input of agrochemicals); • irrigation impacts (salinisation, biodiversity impacts, wetlands); • watershed level assessment of water use impacts.
Nature protection and expansion of protected areas	• Impact of nature protection and its potential future expansion on land availability and residue removal. This requires taking into account biodiversity values of different land types (including marginal land), short term direct and indirect land use changes compared to reference land use system, energy crop choice and management (input of agrochemicals, risk of GMOs, water use, fragmentation, etc); • long term climate change impacts and shifts in vegetation zones; • impact of bioenergy induced eutrophication and acidification; • soil organic matter, detritus and residue removal thresholds; • use of consistent biodiversity indicators (e.g. ecological footprint, natural capital index, mean species abundance, biodiversity intactness index, etc.).
Climate change and GHG emissions	• Impact of net GHG emissions of bioenergy supply chains on sustainable bioenergy potential using state of the art analysis of emission factors; • Impact of fertiliser use, energy crop choices; • accounting for co-products e.g. electricity generation and DDGS; • impact of bioenergy production on direct and indirect land use changes compared to reference land use, soil carbon content and changes; • impacts of CO_2 fertilisation effects, temperature changes, precipitation and water availability changes, desertification and shift in land productivity, and other climate change impacts on bioenergy potential.
Choice of energy crops	• impact of energy conversion efficiency and higher energy yields between woody and herbaceous plants compared to grains and oils; • impact of land requirements (energy yield per unit land), tolerance of different environmental and climate conditions and ability to grow well in marginal soils, avoidance of food-fuel conflicts, as well as agro-inputs requirements.
Use of agricultural and forestry by-products	• Inclusion of good quality (and projected changes in) residue/waste generation factors, residue recoverability fraction, residue availability fraction, harvest index, residue collection technologies and potential improvements; • accounting for competing applications of residues (potential future applications reduce availability for energy); • biodiversity thresholds of residue removal (for maintaining soil fertility and biodiversity); • tillage practices (determine residue removal thresholds where no tillage allows greater removal of residues from fields).
Market mechanism for food–feed–fuel–materials	• Improved models to accurately link prices of food, feed, fuel, biomaterials, land prices, energy prices and increased bioenergy production (increased bioenergy production can lead to increase in agricultural commodity prices, resultantly reducing economic potential of bioenergy); • inclusion of other macro-economic feedbacks.
Cost of biomass production	• Location specific data on land and energy prices, crop yields, energy crop choices, water availability,

Table 2 (*continued*)

Drivers and factors	Main requirements/inputs/aspects to be included for comprehensive potential assessments
	technological learning in crop production; • influence of trade, policies (bioenergy, agricultural and environmental e.g. subsidies), and international agreements on bioenergy markets; • inclusion of dynamic cost supply curve to capture learning and cost variation over time.

Table 3
Land resource categorization.

Land category	Description	Reference
Unused agricultural (arable) land (after fulfilling human and environmental needs)	Surplus agricultural land	[13,6]
	Abandoned agricultural land	[46,105,106,14]
	Unused active cropland, idle cropland, fallow land (e.g. Conservation Reserve Program lands of the US)	[11,47,98]
Low productive land (not suitable for conventional crop growing)	Marginal or degraded land	[13,6,46,92,94,95]
	Remaining suitable land after excluding all agricultural land, unmanaged land with a long carbon payback periods, degraded land, wetlands, environmentally protected land, and land rich in biodiversity	[91]
	Wastelands suitable for energy cropping e.g. in India	[191,188]
	Reserve (arable) lands in China, farmlands returned to forestry, barren hills, degraded forest land	[181]
	Abandoned mine lands	[180]
Unprotected and underutilised lands	Unprotected grassland and woodland, non-forested areas, land held by absentee landlords	[14,189]
	Cropland used as pasture	[11]
	Rest land (remaining area after correcting for human, ecological needs)	[46]
Country specific land types	Land under alternate cropping systems such as agroforestry, public lands along railway tracks, roads and canals.	[188,191]

hydrology and soil structure conditions, such as steep slopes of mountains, or areas with high levels of erosion, or soil with high salt content). Most studies estimate unused and suitable land (after fulfilling food and environmental needs) and analysts use various terms to describe this type of land such as "surplus agricultural land" (e.g. Smeets et al. [13]). The second type of land category is low productive land which incorporates "marginal" and degraded land. Other land categories are also included in various studies as shown in Table 3.

Degraded and marginal land[1] has received special attention because this type of land is partially or not suitable for conventional agriculture, and this helps in limiting competition with food supplies. However, very few studies focus on the bioenergy potential on degraded land because reliable data about soil degradation is not available. Van Vuuren et al. [14], WBGU [91], Wicke et al. [92] and Nijsen et al. [93] are examples of recent studies that use the Global Assessment of Human Induced Soil Degradation (GLASOD) database for selecting areas suitable for bioenergy production. Wicke et al. [94,95] are also recent studies that explore biomass potential on degraded (salt-affected soils) and arid areas (See Section 2.5.5 on soil for further discussion).

2.5.2.2. Competition for land—Factors affecting land availability. Food demand is the most important factor that influences land availability, but other key factors include fibre demand, extent of protected areas, urban areas, water constrained areas and degraded areas. Food demand is driven by population growth and consumption behaviour, as for example, a high meat diet requires more land. Pressure on the available land can be offset by increases in yield, which is a function of technology, management and climate [13,46,96,47,89]. As shown in Fig. 5, competition for land is caused by direct pressures (such as natural degradation and direct land conversion) as well as more subtle underlying drivers (such as demographic dynamics and land policies). All assessments of land availability have in common that they are based on assumptions on how these different pressures on the land resource affect future land use allocation.

2.5.2.3. Approaches to estimating available land. Three approaches to estimating land availability can be identified, mostly based on the "food/fibre and environment first" principle where unused and suitable land is calculated after land requirements for food, feed, fibre and other competing land uses have been fulfilled.

I. Statistical land balance approach
The most common approach is the statistical land balance approach, sometimes incorporating land allocation models. Examples include Smeets et al. [13], Renew [23], Von Braun [97], De Wit and Faaij [28], Van Dam et al. [58], van Vuuren et al. [14] and WBGU [91]. A disadvantage of this approach is high risk of overestimating available land due to lack of spatial detail [58] and underestimating areas used for grazing[2] [98].

[1] According to Wicke [143], p. 5, degraded land is land that has experienced a long term reduction or loss, in its ecosystem function and services (i.e. biological or economic productivity) as a result of disturbances (i.e. physical, chemical and biological deterioration properties of soil) from which the system cannot recover unaided. Marginal land on the other hand is land in which cost-effective food and feed production is challenging under given site conditions and cultivation techniques.

[2] Land used for extensive grazing or pasture land is very difficult to estimate as current estimates are known to be inconsistent [98]. Further, livestock grazing is often underestimated as it is not confined to areas classified as 'pastures' in FAO statistics, but can include many ecosystems such as shrublands and forests. In addition, most livestock kept by subsistence farmers are not captured in official statistics [4,213].

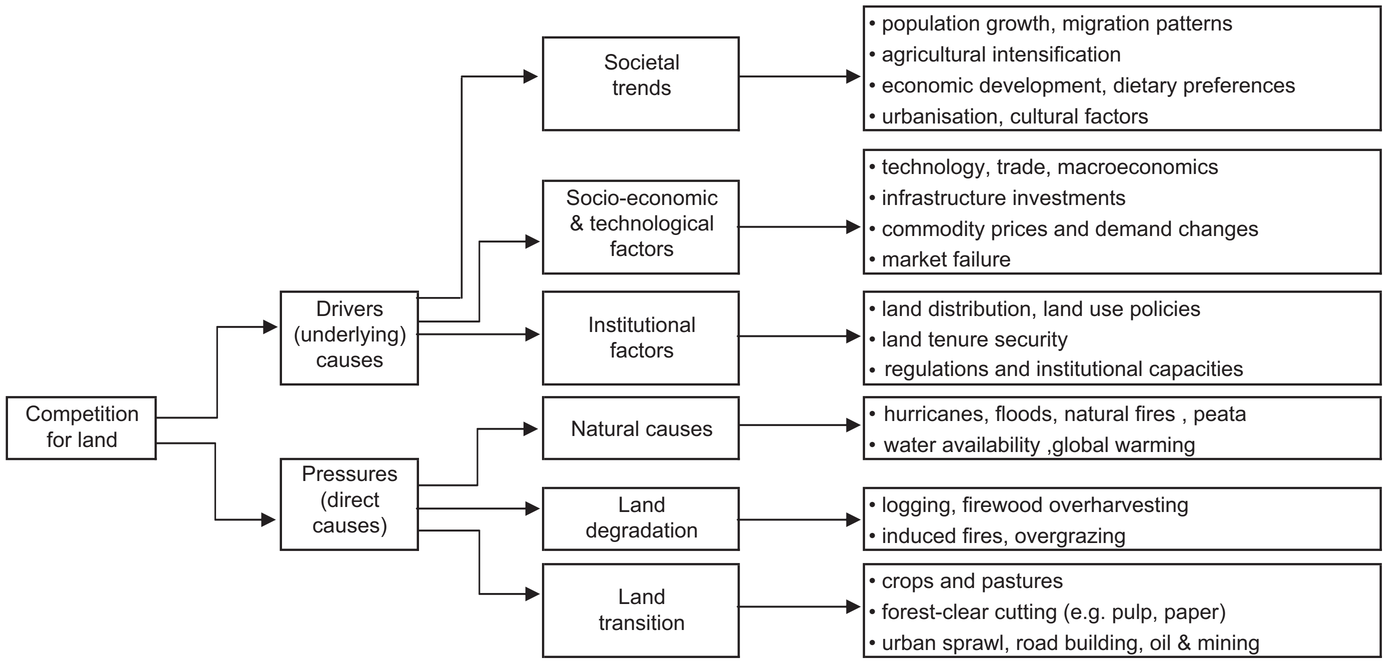


Fig. 5. Overview of factors affecting competition for land.

II. Combined spatially explicit analysis and crop growth models
Some resource-focused assessments use spatially explicit approach in combination with crop growth models that use spatially explicit data on climate, soil type and crop management. For example, Benítez et al. [99] use the International Geosphere–Biosphere Programme (IGBP) land cover dataset to estimate marginal land by excluding "highly productive land" areas with high population density, areas with elevation above 3500 m, and areas with long carbon payback times as predicted by the forest growth model. Other examples include Erb et al. [98], Haberl et al. [4], Krausmann et al. [100], Havlík et al. [101] and Hoogwijk et al. [46]. However, this approach does not explicitly analyse the food–fuel competition for land and other resources.

III. Integrated land use modelling
A more advanced approach employs integrated assessments in which integrated land use models simulate land allocation and accounts for competition among major land-use production sectors. Examples of notable integrated land use models include the IMAGE-GTAP coupled models [64], the JPJmL–MagPIE coupled models [61], GLOBIOM model [102], and the AGLU module in MiniCAM 2.0 [101]. The IMAGE model is one of the most widely used integrated model in recent studies (e.g. Hoogwijk et al. [46]; De Vries et al. [103]; Strengers et al. [104]) to analyse the interaction between the bioenergy sector and other land uses. Another example of a study that integrates environmental (physical) constraints into an economic decision making process is given in Lotze-Campen et al. [61], where the MAgPIE land use model is coupled with the LPJmL dynamic global vegetation model to compute global spatially explicit land-use and water-use patterns.

2.5.2.4. Current land availability estimates. Estimates of long term (2050) global land availability for bioenergy production from recent studies are shown in Table 4. The studies are based on different methods and land use scenarios, but include basic sustainability constraints such as food security, nature conservation, etc. Using the IMAGE model, Hoogwijk et al. [46] estimate that between 600–1500 Mha of abandoned agricultural land and 300–1400 Mha of rest land could be available for bioenergy production. Smeets et al. [13] use the Quickscan model and estimated that 0.7–3.6 Gha of surplus agricultural land could, in theory, be available if improvements in agricultural management are achieved. The assessment of van Vuuren et al. [14] follows the methodology by Hoogwijk et al. [46] and calculates biomass potential on abandoned agricultural lands and natural grasslands to be 1500 Mha. Campbell et al. [105] and Field et al. [106] also estimate potential availability of abandoned agricultural land to be 385–472 Mha and 386 Mha respectively. The German Advisory Council for Global Environmental Change [91] used LPJmL model to assess land suitability for bioenergy crops and estimate that between 240 and 500 Mha of land could be available for energy crop production.

The study by Erb et al. [98] calculates bioenergy potentials on surplus agricultural land using a biomass-balance model and estimate land availability at 230–900 Mha. Fischer et al. [47] modelled land availability for rain-fed energy crops using spatially explicit suitability index and estimate that between 700 and 800 Mha of unprotected woodlands and grasslands could be available.

Land availability for bioenergy production is critically dependent on biomass productivity and related efficient land utilization.[3] The main strategies for efficient land usage include increased efficiency in agricultural crop and livestock production, and integrated food, feed and fuel production [107]. Agricultural crop yield increases can be achieved by improved fertiliser application (e.g. through increasing the amount and/or improving the timing of nitrogen fertiliser application), better weed and pest management, switching varieties grown, investments in agricultural research and development, and multiple rotations (such as conventional crops in

[3] Land use efficiency refers to the level of functional economic outputs (especially agricultural products) per unit land area. An ability to derive more output on a given land area (i.e. intensive production) leads to high efficient land usage. This can be achieved by increase productivity of a particular economic activity or by multiple use of space for several activities.

Table 4
Estimates of land availability for bioenergy crops in recent studies (in 2050).

Reference	(Sustainability) Constraints	Land use types	Land area available (Mha)
Hoogwijk et al. [46][a]	Ensuring food security; protection of biodiversity	Abandoned agricultural land (100%)[**]	Abandoned:
		Rest land (10–50%)[b]	600–1500 Rest land: 300–1400
Smeets et al. [13][c]	Ensuring food security; protection of biodiversity; avoiding deforestation	Surplus agricultural land (100%)	729–3585
Campbell et al. [105]	Ensuring food security; excluded all agricultural lands; protection of ecosystems; releasing carbon stored in forests	Abandoned agricultural land (100%)	385–472
Field et al. [106]	Ensuring food security; protection of biodiversity and ecosystems; avoiding deforestation;	Abandoned agricultural land (100%)	386
Van Vuuren et al. [14]	Ensuring food security; consider water scarcity; protection of biodiversity; avoiding soil degradation	Abandoned agricultural land (75%)	
Grassland (25%)	1500		
WBGU [91]	Ensuring food security; protection of biodiversity; avoiding deforestation; consider water scarcity and avoid competition for water; excluded all agricultural land, unmanaged land with a long carbon payback periods, degraded land, wetlands, and environmentally protected land	Remaining suitable land after excluding all agricultural land, unmanaged land, degraded land, wetlands, environmentally protected land, and land rich in biodiversity.	240–500
Fischer et al. [47]	Ensuring food security; excluded forests, sloping land, and low productive land	Cropland not needed for food, feed and fibre supply.	700–800
Erb et al. [98][c]	Ensuring food security: land needed for food and feed was excluded; forests and unproductive or uneconomic land were excluded	Cropland not needed for food and fibre supply.	230–990
Nijsen et al. [93]	Ensuring food security; avoiding deforestation; excluded forest areas, cropland, pastoral land and urban areas	Marginal and degraded lands	247
Wicke et al. [95]	Protection of biodiversity; forests, wetlands and protected areas were excluded.	Salt affected lands	971

[**] Percentage values indicate the fraction of the land category that is assumed to be put under energy crops in a respective study.
[a] Estimates are for 18 World regions over a timeframe 2050–2100.
[b] 'Rest land' is the remaining land area (from total available land) after taking into consideration 'abandoned agricultural land' and 'low-productive land' and further subtracting/correcting for grassland areas, forest land, urban areas and bioreserves. 'Rest land' includes mainly savannah, shrubland and grassland/steppe. The overall assumption is that energy crop production should not affect food and fibre production, biodiversity protection.
[c] Estimates are for 11 world regions.

the summer and cool season grasses in the winter) [108,109,110]. Increasing livestock production efficiencies is possible through increasing grazing density, increasing pasture productivity, improved feeding practices (e.g., partially replacing forage by more concentrated fodder and higher protein diets, and landless livestock production [110,13]). Dale et al. [108,109] explore the potential of utilising leaf protein concentrate (LPC) recovery and processing in integrated biorefinery scenarios, which can potentially substitute land extensive soya bean meal production currently being used for livestock feeding.

Wicke et al. [107] also argue that land use efficiency can be improved by integrating food, feed and fuel production thereby increasing biomass production per hectare. Examples of integration of different feedstock production objectives into multi-functional land use practices are agroforestry and silvopastoral production systems that combine food, fodder and fuel crop production. Dale et al. [109] consider 'aggressive double cropping' as an option to increase biomass production per unit area. In addition, also the integration of biomass conversion processes and the production of multiple products such as fuels, power, heat, chemicals as well as feed (a concept generally referred to as biorefining) is important for increasing the per hectare output. Examples range from conventional biorefining systems (where e.g. feeding residues from bioenergy production to animals, see e.g. Egeskog et al. [111] for the case of residues from sugarcane ethanol production used in the feed mix of dairy cattle in Pontal, Brazil) to newer types of biorefineries (e.g. lignocellulosic feedstock biorefinery [108,109]).

Current bioenergy assessments and models do not take these land use efficiency measures into account. Dale et al. [109] shows that the impact of substituting soy animal feed with LPC and double cropping can result in 30% less land being used for soy production in the US, and production of 400 billion litres of ethanol on the same amount of land currently being used for agriculture.

2.5.3. Yields

The yield of energy crops per unit land is a crucial parameter when calculating bioenergy potentials [14]. Estimating future crop yields is based on crop yield models and scenario assumptions on progress in agricultural management and this typically results in a range of values. Various approaches are used to estimate crop yields that take into account land productivity, environmental and management factors. Crop growth models commonly used include, for example the IIASA/FAO Agro-Ecological Zones (AEZ) framework

[112,113]. The AEZ model and similar crop growth models are used in several studies (e.g. Hoogwijk et al. [46]; Van Dam et al. [58]; De Wit and Faaij [28]; Eickhout and Prins [114]). These models make use of various datasets including the world climate dataset, the FAO Soil Map of the World, Global Land Cover Characteristics Database and the digital elevation dataset GTOPO30.

The quality and reliability of these data sets including land use data, land degradation status and grazing intensity, is uneven across regions [112] and this is a key problem when assessing biomass productivity. Especially the quality of the world soil map is reason for concern, although substantial improvements to soil information are in progress (e.g. recent updates of the SOTER (Soil Terrain) database).[4] Also it is not possible to infer the status of land degradation from the world soil map. Only a few spatially explicit soil degradation datasets are available at the global scale. These include the Global Assessment of Human-induced Soil Degradation (GLASOD) database [115,93], the Global Land Degradation Assessment in Drylands (GLADA) project [116,117] and the Millennium Ecosystem Assessment (MEA) [118]. According to Nijsen et al. [93], the GLASOD database is the most useful of the currently available datasets to estimate spatially explicit energy crop productivity. However, the GLASOD database is relatively old (published in 1991), it has limited geographical detail and the applied expert method has limitations in reliability and detail [115]. Fischer et al. [119] also argue that GLASOD offers insufficient detail for useful application with crop growth models. Despite these disadvantages, GLASOD remains the most influential global appraisal of land quality [115] and has been used in several studies (including Van Vuuren et al. [14], Dornburg et al. [82], and Nijsen et al. [93]). Wicke et al. [95] offers a comprehensive analysis of biomass potential on saline soils and uses the Harmonised World Soil Database (HWSD) to estimate the global extent and location of salt-affected soils in combination with the Global Land Cover Database for 2000.

A crucial factor when estimating crop yields is the crop management system and the assumed yield growth rate. Also the impact of climatic change is potentially important, although this is often not explicitly investigated. However, crop management can have a relatively larger impact on crop yields than climate change [120]. Therefore, many resource-focussed studies include scenarios that evaluate the impact of technological learning on crop yields and the uncertainty in future yields. This includes both energy crops and conventional crops, since the latter determines future demand for agricultural land. Examples include van den Wall Bake et al. [121] and Hettinga et al. [122]. Yield increase rates for conventional crops are projected to be more limited compared to energy crops [123],[124]. Hettinga et al. [122] estimate that between 1975 and 2005, corn production costs in the US declined by 62% to 100$_{2005}$/tonne, indicating a progress ratio (PR) of 0.55. Van den Wall Bake et al. [121] show a PR of 0.68 for sugarcane production in Brazil over the last 30 years. De Wit et al. [110] show that yield increases are policy dependent and could be rapid for some regions.

The IMAGE model uses the AEZ crop growth model to calculate 'constraint-free rainfed crop yields' based on local climate as well as soil-specific conditions such as nutrient retention and availability; level of salinity, alkalinity and toxicity. Crop yields are adjusted by a management factor that accounts for the future impact of breeding, a higher harvest index, use of irrigation and fertilisers, general (bio)technological improvements and the (limited) effect of CO_2 fertilisation. Smeets et al. [125] also use a crop growth model (MiscanMod) to estimate the yields of miscanthus and switchgrass in Europe between 2004 and 2030. They estimate a non-exponential yield increase of 1.5% yr^{-1} with an uncertainty estimate of $\pm$20% over the period.

Biotechnology and especially the use of genetically modified organisms (GMO) is considered as having potential to improve crop yields [126]. However, no quantitative conclusions have been drawn to date on potential contribution of GMOs, and many uncertainties still remain [127,128] (Table 5).

A weak spot in knowledge concerns the yields of energy crops on degraded areas. Major limitations in current studies include accounting for the potential exacerbation of water shortages in waterscarce regions as well as for the current use and function of degraded and marginal land, especially grazing. Both factors could reduce the potential of sustainable bioenergy production, but the extent to which they would do so is currently unclear. Wicke et al. [95] is one of the few studies that attempt to provide detailed productivity analysis of degraded lands; they employ spatially explicit productivity function that takes into account climate, soil and terrain factors to assess the global technical bioenergy potential on saltaffected land.

2.5.4. Water

Technical biomass potentials can be limited by both the quantity and quality of water available for plant transpiration [129,1,5] and thus biomass productivity. Given reported water constraints in many regions of the world [130–133] water scarcity can limit the expansion and intensification of bioenergy production as well as corresponding energy crops choices [81,131,1,134]. However, on-site water management and careful integration of bioenergy into the current agricultural systems can optimise water utilisation and mitigate water quality impacts [129,134].

Although water availability is often implicitly considered as an important factor in bioenergy potential assessments, very few studies are paying attention to water as a limiting factor and provide insight into spatial and temporal consequences of bioenergy production [135,134]. At the global scale, current studies consider water constraints in bioenergy production based only on precipitation and runoff data, and do not take into account the full water balance on a watershed level. For example, in Hoogwijk et al. [46], energy crop cultivation is restricted to rainfed areas via a so-called land claim exclusion factor and crop yields are linked with climate data in the IMAGE model. However, bioenergy potential assessments that employ spatially explicit biophysical data sets and modelling are able to consider water limitations on land productivity [3] and more accurately assess biomass potentials. Many studies, though, still implicitly presume irrigation development in crop productivity estimates that could lead to competition for water and impaired water quality [131,136].

According to Rost et al. [129] and Malmer et al. [137] explicit geo-hydrological modelling is required to better understand and predict the hydrological effects of various land use options at the watershed level. Such an approach is also able to demonstrate some important opportunities for the bioenergy–water nexus. For example, perennial crops could reduce erosive water run-off, replenish groundwater but may also lead to substantial reductions in downstream water availability [138–140]. Also, a shift to perennial crops can decrease water competition as these crops generally require fewer agronomic inputs and have reduced impacts compared to annual crops [141]. Similarly, strategic selection of crops with a prolonged growing season and a continuous cover may redirect unproductive soil evaporation and runoff to plant transpiration, and reduce soil erosion [81]. This has potential to significantly positively influence local hydrological patterns [134].

[4] See—⟨www.isric.org/UK/About+ISRIC/Projects/Current+Projects/SOTER.htm⟩.

Table 5
Estimated biomass productivities in recent studies.

Study	Type of land	Crop yields (tdm/ha/yr)	Remarks
Smeets et al. [13]	Surplus pasture and farmland	16–21	Based on energy crop yields in IMAGE model, which are based on a crop growth model and data on soil, climate and characteristics of woody energy crops. Yield range vary according to soil suitability (very suitable to not suitable)-which differ for the four agro-management systems studied. Yields on very suitable soils are in the range of 80–100% of MCFY while not suitable yields are in the range 0–20%. 16 t ha^{-1} yr^{-1} is the global average for system 1 (low tech agro-management system) and 21 t ha^{-1} yr^{-1} is for system 4 (high tech agro-management)
Hoogwijk et al. [46]	Abandoned farmland, low productive land and 'rest' land	<3–35	Yields depend on land suitability and climatic factors. Productivity of energy crops on low-productive areas assumed to be below 3 t ha^{-1} yr^{-1}; about 5% of the maximum yield of 55 t ha^{-1} yr^{-1} in IMAGE model while yields on abandoned agricultural land is 35 t ha^{-1} yr^{-1}
Erb et al. [98]	Surplus farmland and pasture	6.4–7	Yields are equal to potential NPP on cropland and NPP on grazing land
WBGU [91]	Rest land	7.5–12.6	Uses LPJmL crop growth model to estimate yields of high-productivity grasses and fast growing trees in short-rotation plantations with and without irrigation
Van Vuuren et al. [14]	Abandoned farmland, degraded natural grassland	2.5–33	Yields depend on land suitability and climate factors using the IMAGE model. Assumes 75% accessibility to abandoned agricultural land and 50% accessibility of grasslands
Field et al. [106]	Cropland, pasture and abandoned farmland	6.8–13.4 (weighted average)	Global average potential climatological NPP of carbon on available lands and based on the HYDE 3 database. Higher yields achieved on category 'in forest' land.
Campbell et al. [105]	Abandoned farmland	4.3 (weighted average)	Represents global area-weighted mean productivity of above-ground biomass. Yields on abandoned lands are highest in regions of tropical grasslands, ranging from 7 to 20 t ha^{-1} y^{-1}.
Fischer et al. [47]	Surplus grasslands and woodlands	6.3–21.8	Rain-fed yields under low to high scenarios averaged for all world regions. Lowest yield estimated is an average for Middle East and North Africa under a low growth scenario, highest yields achieved in Latin America under high growth development scenario
Nijsen et al. [93]	Marginal and degraded lands	5–15 Global weighted average (10.2)	Global average based on geographically explicit GLASOD and IMAGE data. High yields 15 t ha^{-1} y^{-1} estimated for USA, RCAM, Ukraine, Oceania, Korea and Indonesia. Lower yields found in Middle East, South, East and West Africa, and Turkey.
Wicke et al. [95]	Salt affected lands	0–27 Weighted global average (3.1)	Global average woody biomass production from forestry plantations. Yield differences related to severity of salt-affectedness and climate (especially precipitation).

An example of a bioenergy assessment that models global water constraints in a spatially explicit manner is Beringer et al. [5]. The study employs climate driven scenarios to simulate global biomass productivities under different water availability conditions at watershed level using only renewable water resources for rainfed and irrigated crop production. The study shows that irrigation using renewable water resources can increase bioenergy production by 70% on average—compared to rainfed simulations, but agricultural irrigation water use would have to double from current levels of about 2500 km^3 yr^{-1}. Another study by Von Braun [97] models in detail the interactions between water, food and trade in scenarios that represent future climates. This allows for separate area and yield functions for rainfed and irrigated crops; water allocation among crops as well as yield and area reductions from lack of water.

Water stress can also be reduced by enhanced water use efficiency (WUE). Considerable improvements can be realised in WUE in conventional agriculture and, depending on location and climate, for new crops such as perennial cropping systems [82,129,142]. Examples of measures to improve WUE include minimising direct evaporation from soils (unproductive water loss), improving water retention and maximising transpiration (productive water use).

2.5.5. Soil

The quality of available land and its characteristics are also important determinants of bioenergy technical potentials. Soil quality or fertility directly affects biomass productivity (and hence bioenergy potentials) and is influenced by nutrient availability, texture and drainage, pH level and by the input of fertiliser [91,93,95,143,144]. Also, bioenergy potential from residues is affected by the constraints that are imposed on the removal of agricultural and forestry residues, as these residues play an important role for soil structure, soil organic matter (SOM) and soil quality conservation [145–147]. However, the constraints on residue removal depend mainly on the agricultural management practices, soil type and location [3,11,20,23,148–150]. Some cultivation practices, such as conservation tillage and crop rotations, can mitigate adverse impacts of residue removal and in some cases improve environmental benefits of biofuels production [151,149].

The proneness of soil to erosion is another soil characteristic that affects potential land availability for bioenergy production. Typically, erosion susceptibility limits land availability by exclusion of areas above a certain slope, and requires matching crop choices to soil and topographic conditions [152,94,153]. Soil erosion also releases carbon and contributes to nutrient leakage that contaminates water bodies [154,155].

Growing perennial energy crops offers opportunities to utilise lands with poorer soil quality and increases possibilities for reduced nutrient leaching, increased soil productivity and increased carbon sequestration [93,156]. According to Lal [157], soils under perennial crop production have higher SOM than annual crops. Perennial crops limit the removal of SOM through erosion, biological oxidation and leaching, and the accumulation of litter and the extensive root systems contribute to the buildup of SOM.

Some resource-focussed studies use crop growth models that use data on soil quality, but only a few studies include soil erosion vulnerability. In Eickhout and Prins [114], the conversion of land to arable land use is not allowed in erosion sensitive areas. Van der Hilst et al. [60] and Wicke et al. [94] exclude land areas that are unsuitable for energy crop production including steep slopes that exceed 16% and 8% respectively. Dieter et al. [158] exclude areas with more than 60% gradient from forestry use. Productivity of biomass on degraded land is already discussed in Section 2.5.3 and Wicke et al. [95] and Nijsen et al. [93] are recent examples of studies that model energy productivity on degraded and marginal land.

For residues, studies typically use a residue withdrawal threshold to account for soil conservation and biodiversity requirements. For example, Ericsson and Nilsson [20] allowed only 25% of the straw to be harvested while Renew [23] excludes removal of straw required for soil related needs. More complex approaches are applied in Gordon et al. [68], EEA [25] and Valk [150]. Gordon et al. [68] conducts site specific tests for three different tillage scenarios to maintain soil quality while in EEA [25], forestry residues extraction rates are limited to 75% and are adapted to soil characteristics and the level of nitrogen deposition. Valk [150] modelled residue removal using the Rothamsted Organic Carbon Model. The study derives a field threshold residue cover requirement of 2 t/ha for erosion control and estimates that additional residues could be required to maintain at least 2% soil organic carbon in the top 20 cm of the soil depending on the local conditions.

2.5.6. Biodiversity

Bioenergy production has local impacts on biological diversity due to considerations about land use changes, crop management and residue removal; and also global impacts due to climate change. Hence, sustainable bioenergy potentials can be limited by biodiversity constraints set on the expansion of agricultural land area—and thus the area available for energy crops cultivation as well as biomass yields [61]. There is always a risk of biodiversity loss when agricultural land is expanded to areas formerly not used for agriculture, especially where high nature value ecosystems such as undisturbed forests are converted. However, energy crop production also provides opportunities for improving biodiversity, e.g. through restoration of degraded lands.

Biomass resource potential assessments typically exclude nature conservation areas from being available for biomass production, and take the present level of forest ecosystems protection as a minimum requirement. Many resource-focussed studies restrict the cultivation of energy crops to certain areas such as ‘surplus agricultural land’ or marginal land (e.g. De Vries et al. [103]; Hoogwijk et al. [46]; Kline et al. [159]; Siemons et al. [37]).

However, this approach is regarded as too simplistic and insufficient to meet biodiversity protection targets [3]. According to Dornburg et al. [77], the impact of bioenergy production on biodiversity should ideally include the effects of (indirect) land use change—so called (i)LUC and effects of (avoided) climate change. Climate change affects growing conditions substantially and might lead to a shift of vegetation zones, towards higher latitudes, for instance. In contrast, use of bioenergy can mitigate climate change with resultant improvements in global biodiversity.

Energy crop production can improve biodiversity, e.g. when degraded lands are cultivated or when multiple species are planted and mosaic landscapes are established in uniform agricultural landscapes [160]. Energy crops grown on marginal land can assist in restoring or conserving soils, habitats and ecosystem functions [161,95]. Agro–forestry systems, combining biomass and food production can support biodiversity conservation in human-dominated landscapes [162,161]. Such bioenergy plantations can provide ecological corridors for plants and animals [3] and can filter nutrients load from other agricultural activities, reduce eutrophication in water bodies and thereby improve biodiversity [163,141]. However, current bioenergy potential assessments assume crop yields achieved in monoculture settings and do not consider such mixed cropping systems [3].

Biodiversity conservation also limits the extraction of agricultural and forestry residues, and thus the associated technical bioenergy potential. For residues, restrictions involve limiting the harvested area and the amount of residues that is removed. Studies that exclude protected forest areas from residue harvesting include Masera et al. [164] and Kärkkäinen et al. [165]. Limiting residue removal has traditionally been done to protect soil fertility, but it also helps maintain soil ecosystems and protect organisms relying on dead material (Ericsson and Nilsson [20]; Gordon et al. [68]).

Only a few studies account for more comprehensive integration of biodiversity criteria. Examples of such studies include EEA [24,26] and Ten Brink et al. [64]. EEA [24,26] applies several environmental criteria, e.g. the reservation of land-use, exclusion of protected areas, limitation of forest residue removal, and maintenance of ‘ecological compensation area’. Ten Brink et al. [64] assesses the aggregated impact of climate change on biodiversity using a combination of the IMAGE and GLOBIO3 models.

2.5.7. Climatic change

Climate change can potentially affect technical bioenergy potential through two main effects. First, elevated atmospheric CO_2 concentration can increase C3 plants growth (CO_2 fertilisation effect) [166]. Further, elevated atmospheric CO_2 concentrations can improve water use efficiency, and partly counteract increased plant evapotranspiration expected in a warmer climate [167]. Also, changes in weather patterns, particularly precipitation patterns can increase or decrease plant production. Biomass potential could be adversely reduced especially in tropical regions if plants experience increased water stress or nutrient depletion (even with increased water use efficiency under CO_2 fertilisation) [3].

Most studies ignore the impact of climatic change on biomass production potential. Some exceptions include Hoogwijk et al. [46], where crop growth models that include the effect of CO_2 fertilisation are used to predict yields, while land availability is reduced in some scenarios due to effects of climate change. According to WBGU [91], the impact of climatic change on bioenergy yields are limited, when compared to other, more uncertain, factors. However, regional impacts can be severe and many aspects remain highly uncertain [3].

Second, climate change considerations can affect sustainable bioenergy potentials by excluding biomass energy that results in increased GHG emissions. Considerations should be made for entire fuel supply chains to validate the carbon impact of supplying bioenergy from points of production to the markets. This is especially important since climate change mitigation is one of the drivers behind the production and use of bioenergy. The IPCC SRREN report [3] indicates that bioenergy is expected to make significant contribution in several GHG stabilisation scenarios in the long term if sustainability frameworks are implemented.

Several demand-driven studies investigate the demand for biofuels to reach certain climate change mitigation targets or vice versa (e.g. EEA [24,26]; EPA [168]). These studies typically use default emission reduction factors taken from life cycle assessments (LCAs) to estimate the reduction in GHG emissions (e.g. Larson [169]; von Blottnitz and Curran [170]) and thereby ignore several crucial aspects:

- Most LCAs do not take into account emissions from direct and indirect land use changes (so-called dLUC and iLUC) and related carbon stock changes. Several studies have investigated this issue (e.g. Gallagher [171], Fritsche et al. [172]; Edwards et al. [173]; EPA [168]; Hoefnagels et al. [174]), but the results are not yet incorporated in bioenergy potential studies. Especially iLUC impacts are uncertain and difficult to model [3]. Wicke et al. [107] explores and proposes strategies

for mitigating both direct and indirect LUC and its effects, rather than for studies to focus on eliminating uncertainties in evaluating their impact. For example, they propose rationalisation in agriculture and integrating biomass production to reduce LUC impacts.
- Nitrous oxide (N_2O) emissions can have a drastic impact on the GHG balance of biofuels [175,176], mainly related to nitrogen fertiliser application. Agriculture is the biggest source of N_2O [177] and about one-third of agricultural N_2O emissions are due to newly-fixed nitrogen fertiliser [3]. But approaches to calculate N_2O emissions (such as proposed by Crutzen et al. [178], the IPCC Tier 1 approach and recent modelling by Davidson [179]) are not consistent due to consideration of different assumptions.

Exclusion of these aspects typically leads to an underestimation of the environmental impacts of bioenergy supply and thus an overestimation of the sustainable bioenergy potential.

3. Lessons learnt from reviewing and harmonising biomass country studies

A review of selected country based biomass energy potential studies was conducted to establish the range of bioenergy resource potentials in five selected countries up to the year 2030. The countries considered include China, India, Indonesia, Mozambique and the United States. The selection of these countries was made to reflect regional bioenergy production potential diversity, market development and policy differences. This section discusses the lessons learnt during the review exercise vis-à-vis the methodological review of Section 2 and demonstrates the difficulties that are usually encountered when one attempts to harmonise different national studies and establish credible national bioenergy scenarios.

The features of an ideal study discussed in Section 2 provide the basis for identifying and comparing key criteria included in each of the bioenergy potential assessments that were reviewed. We use the following checklist (given also in Table 6) to verify and compare aspects that have been included or omitted in each study:

- Biomass demand for food, feed, fibre and biomaterials.
- Improvements in agricultural and forestry management and technologies.
- Use of marginal and degraded land.
- Water availability and use.
- Nature protection and expansion of protected areas.
- Climate change and GHG emissions.
- Use of agricultural and forestry by-products.
- Market mechanism for food–feed–fuel–materials.
- Cost of biomass production.

Selection and screening of studies

Many studies focus on the final outcomes of the national biomass resource and provide limited insights into the methodology, assumptions or parameters employed. When this is the case, it becomes difficult to interpret the results of such studies or normalise such results as there is no basis for such an evaluation. Such studies were therefore excluded from the analysis.

Screening of studies was followed by evaluating the methodology, parameters and key assumptions used in each selected study. The datasets were then compared with the baseline and normalised over a common timeframe. In this instance, the reference period was set to year 2030. Below is an analysis of lessons learnt from various country studies.

3.1. Review of bioenergy potential assessments in the US

Several studies have been conducted in the US to assess the biomass energy resource (notably Perlack et al. [11]; Parker et al. [66]; Milbrandt [180]; USDoE [32]). These studies provide detailed potentials of biomass energy based on state of the art techniques and modelling approaches. However, the methodology, geographical scope, assumptions and type of resources analysed differs by study. Compared to other countries, US studies are more comprehensive and use state of the art analysis. Furthermore, availability of country specific data and historical trends enable better understanding of the correlations between socio-economic and bio-physical interactions.

3.1.1. Approach

For the US, the so-called "Billion ton study" report [11] and its updated version [32] are the key reference documents as they provide a detailed national scope. These assessments are demand driven studies that use bottom-up statistical analysis to provide comprehensive national potential analysis of the key biomass energy resources in the US up to 2030. Other studies provide more detailed and geographically constrained analysis. For example, Milbrandt [180] provides more data on biomass resource availability for each state, although it is less transparent in terms of assumptions and key parameters used in its assessment. The study by Milbrandt [180] is a resource focussed assessment that evaluates the technical biomass resource potential using both statistical analysis and spatially explicit geographic information systems (GIS). Parker et al. [66] is a regional study (western US states) which builds on the earlier reports (such as Perlack et al. [11]) and adds cost supply dimension to the analysis. It is a short term study and focuses on economic biofuels potential in 2015. Parker et al. [66] is also a resource focussed study that combines optimisation methods from operations research (for logistic optimisation) and GIS analysis into an integrated model of the biofuels industry.

3.1.2. Biomass demand for food, feed, fibre and biomaterials

Perlack et al. [11] and USDoE [32] investigate the technical feasibility of a billion-tonne annual supply of biomass as feedstock for a bioenergy and bioproducts industry, taking into account the demand for land and competing biomass applications. They illustrate the capability of the country to meet its bioenergy targets and gives clear indications via scenario analysis, the necessary conditions to achieve given biomass potentials. A major source of disparity with other studies is the inclusion in the estimated potentials of biomass that is captive to existing uses. For instance, of the estimated forestry sector biomass potential of 368 Mt, 40% is already utilised but included in the total potential (under the assumption that the resource could be diverted from its captive use to the new application). In such a case, the total potentials are reduced correspondingly to reflect the unused available resource.

Generally, the studies attest to incorporating some basic sustainability criteria such as avoiding future food fuel conflicts and excluding protected areas. However, competition between biomass for energy and materials with food, wood products and other energy carriers as well as competition for water and land resources are not explicitly analysed. Also, human diets and possible alternative protein chains are poorly included (or not included at all as in Milbrandt [180]), while the impacts of different animal production systems were not assessed in detail.

Table 6
Comparative evaluation of selected biomass energy potential country assessments.

Country studies/drivers and factors		Biomass demand for food, feed, fibre, and biomaterials	Improvements in agricultural and forestry management and technologies	Use of marginal and degraded land	Water availability and use	Nature protection and expansion of protected areas	Climate change and GHG emissions	Use of agricultural and forestry by-products	Market mechanism for food-feed-fuel-materials	Cost of biomass production
China	Sun [181]	✓	✓	✓	✓—not explicit	✓	✓[a]	✓	X	✓
	Kline et al. [159]	✓	✓	X	X—only qualitative discussion	✓	X – not explicit	✓	X	✓
	CAREI [182]	X—assumptions not explicit	X	✓—implied	X	✓—alluded to	X	✓	X	X
	Junfeng & Runqing [183]; Junfeng et al. [184]	✓	X	X	X	X	X - alluded to	✓	X	✓
	Liu et al. [185]	✓	X	X	X	X	✓[a]	✓	X	X
	Tian et al. [186]	✓	X	✓	X	✓	X	X	X	X
	Qui et al. [187]	✓	✓	✓	X	✓	X	X	X	X
India	TERI [188]	✓	X alluded to	✓	X—not explicit	X—only alluded to	✓[a]	X	X	✓[b]
	IRG [189]	✓	X	✓	✓	✓	✓[a]	✓	X	✓[b]
	Sudha and Ravindranath [190]	✓	✓	✓	✓ impact of competition not assessed	✓	X	✓	X	X
	Ravindranath and Balachandra [191]	X—not explicit	X	✓	X—not explicit	X not explicit	X	✓	X	x
	Ravindranath et al. [192]	✓ competing applications assessed	–	–	–	X—sustainable use is assessed	X	✓	X	X
	Schaldach et al. [193]	✓	✓	✓	✓	✓	X	X	X	X
	Rajagopal [194]	✓	X	✓	✓	X not explicit	X	X	X	X
	Ramachandra et al. [195]	X	X	✓	X	X	X only alluded to	✓	X	X
	Ravindranath et al. [196]	✓—not explicit	X	✓	X—only alluded to	X—not explicit	✓[a]	X	X	✓ assumptions not explicit
Indonesia	Suntana et al. [198]	X—alluded to	X	X	X	✓—implied	X – alluded to	✓	X	X
	Duryea [199]	X—not explicit	X	X	X	X—alluded to	X	✓	X	X
	Kamarrudin [200]	✓—alluded to	X	X	X	X	X – alluded to	✓	X	X
	ADB [201]	✓	X	X	X	X	✓	✓	X	✓
Mozambique	Batidzirai et al. [205]	✓	✓	✓	X	✓	✓[a]	✓	X	✓
	Hoyt et al. [206]	✓	✓	✓	X—not explicit	✓	✓[a]	X	X	✓
	Vasco and Costa [207]	X	X	X	X	X	X alluded to	✓	X	✓ not explicit
	Van der Hilst and Faaij [208]	✓	✓	✓	✓ not explicit	✓	X	X	X	✓
US	Perlack et al. [11]	✓	✓	X	X	✓	X	✓	X	X
	USDoE [32]	✓	✓	X	✓ not explicit	✓	X	✓	✓ not explicit	✓
	Parker et al. [66]	✓ not explicit	X	implied	X	✓	X	✓	X	✓
	Milbrandt [180]	✓ although not explicit	✓	✓	X	✓	X	✓	X	X

Key:
✓—aspect is included in study.
X—aspect is not included in study.

[a] LCAs of various biofuels/supply chains discussed but the impact o climate change on bioenergy potential is not assessed.
[b] No cost supply curve is provided.

3.1.3. Improvements in agricultural and forestry management and technologies

While Perlack et al. [11] and USDoE [32] takes into account expected learning[5] rates in agricultural production systems (including genetic alteration), recoverable fractions of agriculture and forestry residues and impacts of no-tillage systems on biomass potentials, Milbrandt [180] focuses more on short term potential based on 2002 national statistics and current technologies. In their estimates, Perlack et al. [11] assume that from 33 to 68% of corn stover can be removed from the field (depending on degree of no tillage cultivation), and also residue recovery capabilities of 40–60%; whereas Milbrandt [180] assumes that only about 35% could be collected (to protect the soil under normal tillage) and that recovery rates are 100%. In USDoE [32], agricultural residues are estimated using POLYSYS, a policy simulation model of the US agricultural sector. Sustainably removal rates are estimated from application of Revised Universal Soil Loss Equation (RUSLE2) and Wind Erosion Equation (WEPS) models incorporating the soil conditioning index and tillage. For dedicated energy crops, Perlack et al. [11] allow for 10% harvesting losses at productivities of 11–18 tdm/ha, of which 7% is assumed to be used for other non-energy applications. Parker et al. [66] takes into account technological learning in their cost supply models by assuming cost decline for conversion technologies in 2015.

3.1.4. Use of marginal and degraded land

Perlack et al. [11] identifies up to 181 million hectares (Mha) of land that is potentially available for biomass production in the US, including 138 Mha of 'surplus' active cropland, 15.8 Mha of idle cropland (including land enroled in the conservation reserve programme(CRP)), and 27 Mha of cropland used as pasture. Only 60 Mha are taken into account in the technical potential estimates representing conversion of 16–24 Mha to perennial crops. In USDoE [32], permanent pasture is allowed to convert to energy cropland at a rate of 5% per year up to a maximum of 50% of land per county, but use of CRP lands is not permitted. Although CRP lands can be considered marginal land, these lands are actually fallow cropland which is returned to conventional agriculture after some time. Milbrandt [180] is the only study that evaluates the potential of using abandoned mine lands (considered degraded land) for biomass production. However, the study does not give details of the extent and nature of land used under energy crops. Parker et al. [66] does not indicate the type of land quality on which biomass is cultivated, although it alludes to the increasing role of marginal lands for the production of herbaceous biomass.

3.1.5. Water availability and use

Perlack et al. [11] give average national yield values of food crops and energy crops and do not discuss water availability as a constraint. However, USDoE [32] takes water availability into account by restricting biomass production to rain-fed areas. Milbrandt [180] takes into account ecological zoning and climate conditions combined with elevation and soils as well as human land use interactions in its approach, but the analysis is not explicit.

3.1.6. Nature protection and expansion of protected areas

Apart from USDoE [32], the other studies do not explicitly analyse nature protection and restrictions on residue removal are linked more to the need to maintain soil quality. In contrast, USDoE [32] assumes best management practices (BMPs) in energy crop production and residue removal operations. These measures are directly linked to soil carbon preservation and biodiversity protection. In addition, it is assumed that energy plantations would provide habitat diversity and provide riparian buffers. All the studies do not take into account the possibility of expansion in protected areas.

3.1.7. Climate change and GHG emissions

None of the studies consider climate change impacts on biomass potential or vice versa. Only USDoE [32] makes reference to the need for carbon sequestration.

3.1.8. Use of agricultural and forestry by-products

All the selected studies explore all key agricultural and forestry residues and wastes, including primary, secondary and tertiary streams. Milbrandt [180] also estimates biomass energy potential from methane from municipal solid waste (MSW)/landfill gas, domestic wastewater and manure. But the study does not estimate potential biomass from fuel treatment from forests, food processing residues and first generation biofuels from grains and oil crops.

3.1.9. Market mechanism for food–feed–fuel–materials

No integrated assessment is performed for any of the US studies, e.g. the impact of large-scale biomass production on the prices and demands for land and food was not analysed. However, USDoE [32] models the demand and supply of biomass commodities including pulpwood as well as land use allocation for various competing demands.

3.1.10. Cost of biomass production

Perlack et al. [11] and Milbrandt [180] do not examine the economics of biomass production. Costs supply estimates of biomass are covered in USDoE [32] and Parker et al. [66]; the former provides detailed cost supply curves for the whole country while the latter provides regional cost estimates that include logistics costs as well.

3.2. Review of bioenergy potential assessments in China

Biomass energy potential in China has been studied by several analysts in recent years. The most important studies include Sun [181], Kline et al.[159], CAREI [182], Junfeng and Runqing [183] Junfeng et al. [184], Liu et al. [185], Tian et al. [186], and Qui et al. [187]. In this analysis we focus mainly on the first three studies, because they provide more explicit insights into the methodology and assumptions used in the assessments. Nevertheless, reference to the other studies is made in the following discussion. None of the studies attempt to address all key potential biomass resources, and most of the studies focus on first generation technologies, although several studies evaluate potential from primary agricultural and forestry residues.

3.2.1. Approach

Generally, the studies provide national technical bioenergy potentials based on statistical analysis, with limited spatially explicit assessments and advanced GIS modelling. Economic potential and cost of production analysis is generally limited, as is inclusion of ecological impact aspects. Data on agricultural and forestry activities is not a major constraint in the analysis. Results from field trials on new energy crops are also available.

Sun [181] is a resource focussed assessment that employs statistical analysis on regional land use information plus cost of supply analysis to estimate the technical production potential of

[5] Technological learning is implied by scenario analysis, where crop yields are expected to increase and technological efficiency is expected to improve.

first and second generation ethanol in 2030. The exploratory demand driven study by Kline et al. [159] provides a broad assessment of bioenergy resource potential for several countries including China and India following mainly methodology developed by Perlack et al. [11]. The study examines first generation feedstocks (grains and sugar crops) as well as lignocellulosic feedstocks (agricultural residues and perennial woody crops). Unlike Sun [181] which uses official national land statistics, Kline et al. [159] relies on land availability data from global database FAO Terrastat and FAOSTAT.

3.2.2. Biomass demand for food, feed, fibre and biomaterials

Most of the studies take into account the post-2007 Chinese policy shift to non-food crops and lignocellulosic feedstocks due to concerns about food fuel conflicts. Kline et al. [159] is an exception, as they argue that about 2–30% of the projected corn production could be available as biofuels feedstock in 2027 (assuming high cereal yield growth).

There are different estimates of the proportion of fuelwood that could be diverted from its current uses to modern applications. Junfeng et al. [184] assume that 40% of fuelwood can be saved by efficiency improvements and fuel substitution. Kline et al. [159] assumed 50% of the fuelwood production reported by FAO for 2005 could be available as biofuels feedstock (a rather arbitrary claim), while CAREI [182] assumes all fuelwood from regional forestry stocks is available for bioenergy; but this is highly unlikely unless alternative fuels are provided to the majority.

3.2.3. Improvements in agricultural and forestry management and technologies

Kline et al. [159] do not indicate the type of perennial energy crop assumed in the analysis, but provide a conservative average annual biomass productivity of 4.5 tdm/ha/yr and 50% sustainable recovery (associated with marginal land); but Sun [181] assumes switchgrass at productivities of 13–16 tdm/ha/yr (on surplus agricultural land) and 6–8 tdm/ha/yr (on marginal land). Harvesting losses are estimated at 15%, other studies do not indicate any harvest losses. Technological learning is assumed by Kline et al. [159], Sun [181] and Qui et al. [187], with regard to feedstock production. However, Sun [181] and Kline et al. [159] assume that cost parameters remain constant until 2030, indicating no learning in conversion.

3.2.4. Use of marginal and degraded land

According to Sun [181], China created "reserved lands" in each region to protect agricultural land from unfettered urban and industrial expansion. Biomass could be grown on these "reserved arable lands". Reserved arable lands include arable barren grassland, arable saline land, arable marsh land, arable reed bed and arable shoal land. Reserved reclaimable lands are reclaimed from the lands destroyed by construction or industrial activities. However, reed beds and marsh lands are excluded from energy crops cultivation as they are considered sensitive ecosystems. These reserved lands are generally of low-quality, but are potentially suitable for growing perennial biomass energy crops.

Sun [181] assumes that about 126 Mha of marginal land[6] in China could potentially be available for biomass production. More conservative estimates by Qui et al. [187] allocate only marginal land of 6.7 Mha for bioenergy production (although we considered this estimate to be too low). Sun [181] also assumes that current agricultural land will continue to stabilise around 120 Mha and that all the currently unused land is also available in 2030—this is a result of land protection policies and not directly related to efficiency improvements in agricultural management and technology. In contrast, Kline et al. [159] consider only 10% of available land to be allocated for bioenergy by 2027, which is conservative but a more realistic projection.

Also Sun [181] provides some vital statistics on contiguous reserve lands (which is useful for practical establishment of large scale biomass production than global aggregated data which in practice could be fragmented). However, there are some weak spots in the land use data, and there is also uncertainty about the current use of this land as well as specific government intentions.

3.2.5. Water availability and use

The impact of competition for water or its availability is also not studied in detail in any of the studies. This is critical for the successful large scale cultivation of biomass especially for a water constrained country like China. Only Sun [181] provides some limited qualitative analysis where the high technology scenarios assume the successful development of the South–North water transfer project to enable irrigation and achieve higher yields.

3.2.6. Nature protection and expansion of protected areas, climate change

Only a few sustainability criteria are taken into consideration by the studies, notably ensuring that bioenergy production does not lead to food insecurity, avoiding encroaching on protected areas, and excessive residue removal. Most studies do not indicate the type of land areas excluded, although Sun [181] explicitly excludes all sensitive ecosystems (marsh land and reed beds). Other environmental issues such climate change impacts are not taken into account.

3.2.7. Use of agricultural and forestry by-products

CAREI [182] evaluated current and short term (up to 2020) bioenergy potential from agricultural and forestry waste. The study gives a high availability fraction of agro-residues for energy of 48% compared to Sun's [181] 10–15.6% (but a much lower forestry residue availability of 43% compared to 86% for the latter). Recoverability of all agricultural residues (under conventional tillage practices) and agro-processing residues is assumed to be 25% and 100% respectively by Sun [181] and 33% for corn stover by Kline et al. [159]. Other studies provide estimates of the proportion of residues available for energy but imply 100% recoverability of residues.

3.2.8. Market mechanism for food–feed–fuel–materials

None of the studies analyse the potential market response to large-scale biomass production on the food, feed and other bio-based product markets.

3.2.9. Cost of biomass production

Sun [181] and Kline et al. [159] provide some basic cost of supply indications. None of the studies however, attempt to model the impact of bioenergy production on other markets.

3.3. Review of bioenergy potential assessments in India

Several studies have been conducted to estimate the biomass energy potential given the natural resources of India. Key studies include Kline et al. [159], TERI [188], IRG [189], Sudha and Ravindranath [190], Ravindranath and Balachandra [191], Ravindranath et al. [192], Schaldach et al. [193], Rajagopal [194], Ramachandra et al. [195] and Ravindranath et al. [196]. Similar to the Chinese assessments, most of the studies focus on first

[6] This includes 57 Mha of non-forested areas, 15 Mha of farmlands returned to forestry, as well as 54 Mha of barren hills and wastelands suitable for forestry.

generation bioenergy technologies and generally fail to study all key potential bioenergy resources. Except for Ramachandra et al. [195], all the studies provide national bioenergy potential assessments, without examining the regional distribution of biomass resources. The studies provide limited economic analysis of biomass production (e.g. TERI [188]).

3.3.1. Approach

Kline et al. [159] also made an bioenergy assessment of China and the approach used is the same for India. Sudha and Ravindranath [190] is a resource focussed assessment that employs spatially explicit and statistical analysis which takes into account biophysical conditions and technological scenarios to estimate bioenergy potential in India. It also attempts to address important sustainability elements in its scenario analysis up to the year 2030. Another resource focussed study, IRG [189], uses scenario based statistical analysis to estimate bioenergy potential up to 2040 for several Asian countries (including China, India and Indonesia).This study evaluates potential from a unique biomass resource—'wasted' grain[7] for ethanol production using FAO production data. TERI [188] is a demand driven study which combines agro-ecological zoning techniques with statistical analysis to evaluate the technical potential of first generation biofuels in 2030. Ravindranath et al. [192] is a resource focussed assessment that evaluates the technical biomass from residues (mainly agricultural) using statistical analysis developed in Bhattacharya et al. [197].

3.3.2. Biomass demand for food, feed, and fibre/biomaterials

Basic sustainability criteria (such as minimising food fuel conflicts, excluding protected areas and competing biomass application claims) are taken into account by the majority of studies, although key parameters/assumptions used such as population projections and food demand are not explicitly discussed.

For studies that assess production of energy crops, food-fuel conflicts are avoided by the use of wastelands (e.g. TERI [188], Sudha and Ravindranath [190], Ravindranath and Balachandra [191] and other types of unused arable land. For instance, IRG [189] assumes production of biomass from 'underutilised' lands.

For residues and waste, consideration is also given for competing applications in the studies. According to Sudha and Ravindranath [190] the potential of timber processing waste is limited in India. Due to fuelwood scarcity, forestry residues are normally sold in local markets or collected for free by the local communities. In addition, the study assumes that sustainable wood extraction from forests is highly unlikely as current extraction is unsustainable, the resource is fragile and potential harvesting impacts on the ecosystems could be adverse. Kline et al. [159] use FAO data on non-coniferous roundwood production to estimate forestry industry waste, but ignore competing applications. The study also assumes that 50% of current fuelwood could potentially be available for future bioenergy feedstock (on condition that alternative fuels are available).

Ravindranath et al. [192] assume that only ligneous residues are likely to be available for use as an energy source as most crop residues are used for cattle feed (47% due to poor pasture), fuel for cooking (35%) and thatching. Further, about 40% of dung is used as cookstove fuel, 3% for biogas production and 38% is potentially available for energy.

3.3.3. Improvements in agricultural and forestry management and technologies

Only Sudha and Ravindranath [190] and Schaldach et al. [193] include improvements in agricultural productivity in their assessments. Eucalyptus dominated plantations are the energy crop of choice in Sudha and Ravindranath [190] with biomass productivities vary from 2 to 17 tdm/ha/yr from arid to humid regions (also considering improved agricultural systems and plant breeding). IRG [189] assumes that only 1–5% of 'underutilised' lands could be designated for biofuels, with varying levels of productivity based on the so-called "M3 cropland dataset."[8] In order to meet India's 20% blending requirements, TERI [188] projects that energy crop yields should on average increase to 5 t/ha over 38 Mha of wastelands.

3.3.4. Use of marginal and degraded land

There are widely varying estimates of the extent of available land for bioenergy production in India, especially the amount of available wastelands. According to Kline et al. [159] there is no surplus agricultural land in India as all the 170 Mha of land available arable land is already under cultivation.[9] One thing is certain though, India's growing population (projected to reach 1.5 billion in 2030 according to Smeets et al. [13]) will continue to put pressure on its land and water resources. Given the limited land resource base, India will mainly depend on its wastelands and residues to develop its biomass energy potential [188].

Wastelands in India represent marginal lands with energy crop production capacity, but definitions and estimates differ. Ravindranath and Balachandra [191] estimates that at least 35 Mha out of 107 Mha of degraded land could be available for bioenergy production. But according to Rajagopal [194] only 17 Mha of the 63.9 Mha of wastelands is considered to have the potential for cultivation with crops like Jatropha. By synthesising data from the various studies, the extent of cultivable/culturable wastelands is estimated at about 30–64 Mha, surplus agricultural land (14–27 Mha) and up to 13.4 Mha of other land categories. However, it remains uncertain how much of the wastelands are utilised for other purposes such as pasture. The quality of such lands is also very uncertain.

3.3.5. Water availability, nature protection and climate change impacts

Most of the studies do not incorporate environmental constraints such as water availability, biodiversity protection or climate change constraints. IRG [189] acknowledges qualitatively that water availability could severely reduce estimated potentials, particularly in India and China. Other studies implicitly take water shortages into consideration, e.g. Sudha and Ravindranath [190] use rain-fed yield levels for eucalyptus plantation potential (thus assuming no irrigation due the uncertainty in water availability).

3.3.6. Use of agricultural and forestry by-products

Only TERI [188] and Schaldach et al. [193] do not assess the use of by-products in their assessment of bioenergy potential. Most studies, however, indicate the limited availability of agricultural

[7] A fraction of harvested grains is wasted due to inefficiencies in collection, processing, and transportation. For Asia, about 1–7% of various crops are wasted and recovery factor of 5–15% are assumed.

[8] M3 datasets provide more accurate spatial country–crop combination yield ranges and area coverage maps for 175 crops (as opposed to using single number yields) by combining 22,000 global agricultural censuses reports with recent global maps of croplands.

[9] However, other studies such as Sudha and Ravindranath [190] estimate that 43 Mha (with poor productivity) could potentially be available for biomass production. TERI [188] also identifies 13.4 Mha of special land types such as fallow lands, alternate cropping systems, land held by absentee landlords, etc. which could be used for mostly first generation energy crop development.

and forestry by-products due to competing applications. Also, using FAOSTAT crop production data, IRG [189] argues that only 5–15% of the primary agricultural residues are recoverable due to expected logistical challenges. No study has attempted to estimate tertiary forestry residues in India.

3.3.7. Cost of biomass production

TERI [188] gives estimates of cost of biofuel production from sugarcane and Jatropha while IRG [189] provides production cost estimates for various biofuels from many countries. Ravindranath et al. [192] also provide some limited cost figures for biomass from waste including an estimate of 'economic' bioenergy potential from waste. However, none of the studies attempt to provide a national bioenergy cost supply curve.

3.4. Review of bioenergy potential assessments in Indonesia

There are a limited number of studies that have assessed the biomass energy potential of Indonesia in recent years and these are mainly resource focussed assessments. Examples include Suntana et al. [198], Duryea [199], Kamarrudin [200], IRG [189] and ADB [201]. No study has attempted to examine all potential biomass resources available in the country, and most of the studies only assess specific feedstocks using simple statistical analysis. There has been no assessment of the potential of perennial bioenergy feedstocks in Indonesia and most studies focus on first generation crops, especially oil palm, jatropha and sugarcane. None of the studies assess the cost of biomass production or the impact of improvements in agricultural management on biomass potentials.

3.4.1. Biomass demand for food, feed, and fibre/biomaterials

Most of the studies focus on bioenergy potential from residues, and only IRG [189] estimates bioenergy potential (sugarcane based ethanol and jatropha based biodiesel) using new, currently "underutilized" lands. This limits the impacts of bioenergy production on food and other biomaterials.

3.4.2. Use of agricultural and forestry by-products

All studies evaluate primary agricultural residues for bioenergy, and the potential estimates fall within the same range (although assumptions underlying the estimates are not given). Key crop residues include bagasse, rice straw, coconut and palm residues. According to Kamarrudin [200] and Duryea [199], 90% of the 8 Mt of bagasse are used in sugar factories for captive cogeneration and paper making. About 4 Mt of cane tops and leaves are not being utilised. Most of the molasses are exported, some are fermented into alcohol, and the rest are used as cattle feed. Oil palm fruit harvesting and processing generates residues: empty stalks, fibre and shells, most of which are burned as fuel in palm factories while the cake generally serves as an ingredient in cattle feed. Duryea [199] and Kamarrudin [200] estimate that over 8 Mt of palm residues are produced annually based on industrial statistics. About 6.7 Mt of coconut husks are usually left on the field, but some are used for matting while 3 Mt of shells are used as fuel for drying copra. The presscake is mainly used for feed. Febijanto [202] points out that agricultural wastes are generally scattered and could present logistical challenges to realise potential (except for rice husks). According to Kamarrudin [200], there are 66 Mt of rice residues available every year comprising 12 Mt of husks, 2.5 Mt of bran, 2 Mt of stalks and 49 Mt of straw. Rice stalks and straw are mostly left rotting in the field sometimes after burning, or is ploughed back into the soil as a conditioner and organic fertiliser. In some cases it is used as cattle feed or raw material for paper industry. Some rice husks are burnt as fuel in large rice mills while significant quantities are used as cattle feed. IRG [189] also include potential from "wasted grain"—assumed to be 7.1% of total production for maize and between 1 and 7% for other crops.

Suntana et al. [198] combine national aboveground biomass from various sources including FAO to estimate potential extractable forestry based biomass. They consider only 5% of the national biomass stock can be harnessed. However, this is likely to be controversial, given Indonesia's rapid deforestation rates (the country loses about 1.6 Mha of forest cover annually). From a survey of sawmills in Central Java province, ADB [201] estimates that between 20 and 50% of production input results in waste (mainly log ends, bark, slabs, lumber edge, sawdust).[10] Larger factories use timber waste to generate steam for process drying (although the proportion used is not clear). Duryea [199] argues that most of logging debris is left in the forests and only a small part of these residues are used as fuel.

3.4.3. Improvements in agricultural and forestry management and technologies

None of the studies on Indonesia explores the potential impacts of improvements in technologies and management to bioenergy potentials.

3.4.4. Use of marginal and degraded land

Indonesia is a highly populous island (with average population density is 134 people/km^2) and some islands such as Java and Sumatra no longer have room for arable land expansion. Expansion of agricultural activities is limited by the existence of high nature value forests and peatlands [203]. Given this background, Indonesia is likely to produce sustainable bioenergy from marginal and degraded land. However, there are widely varying estimates of the amount of degraded land available in Indonesia, ranging from 12 to 74 Mha. An illustration of how much degraded land estimations vary is given by Wicke et al. [92]. This variance is mainly attributed to different methods and definitions used to identify degraded land. It is also attributed to issues related to policy and the increasing complexity of the direct and indirect causes of degradation [204]. IRG [189] estimated that over 16 Mha of currently "underutilised" (and thus considered marginal) lands could support high-yielding first generation crops.

3.4.5. Water availability and climate change impacts

None of the studies account for water competition in their estimates of biomass potentials. Climate change is alluded to in Suntana et al. [198] and Duryea [199], but the studies do not assess the potential impacts of climate change on biomass potentials.

3.4.6. Nature protection and expansion of protected areas

A key sustainability concern is the existence of high nature value forests, peatlands and rich species diversity in Indonesia's tropical rain forests. These issues have raised international opposition to oil palm expansion on forestland and an international outcry over oil palm derived biodiesel. Current biomass resource assessments on Indonesia are not explicitly taking into account these and other sustainability concerns such as water and climate change impacts. The focus on residues and waste could explain why analysts steer away from land dependent resources such as perennials. Degraded land could be a solution to this. However, some of the degraded land may be within sensitive ecosystems.

[10] A lot of wood waste is generated by the wood industry, but only part of this waste is actually recycled.

3.4.7. Cost of biomass production

ADB [201] is the only study that attempts to give an economic analysis of bioenergy production, although the derivation of feedstock supply costs is not transparent.

3.5. Review of bioenergy potential assessments in Mozambique

A few studies have been conducted to assess the biomass energy potential in Mozambique. The most important studies include Batidzirai et al. [205], Hoyt et al. [206] and Vasco and Costa [207] and van der Hilst and Faaij [208].

3.5.1. Approach

None of the studies assessed all potential biomass energy resources. The three national studies focus on primary agricultural biomass resources while the regional study [207] partially analyses forestry residues. Secondary and tertiary resources have not been evaluated in detail. Batidzirai et al. [205] is a resource focussed study that assessed the technical biomass energy potential in Mozambique, its production economics as well as logistic options for Mozambique to produce and export biofuels. Van der Hilst and Faaij [208] uses spatially explicit GIS datasets to establish cost supply curves for Mozambique up to 2030. Both studies focused mainly on the production of SRC energy crops (using eucalyptus as an example). Hoyt et al. [206] is also a resource focussed assessment and it provides a more conservative national implementation potential focussing on a transition trajectory that takes into account implementation constraints. Vasco and Costa [207] only evaluate forest biomass residues in Maputo province using official government GIS data and forest growth rates data.

3.5.2. Biomass demand for food, feed, and fibre/biomaterials

Batidzirai et al. [205] use a bottom up approach for evaluating land availability and suitability for growing dedicated energy crops and bioenergy potential production based on a methodology developed by Smeets et al. [13]. It is assumed that competition between food and bioenergy production is avoided and therefore, food production is given priority in land allocation. Land for bioenergy production is limited to surplus arable land and it is assumed that additional surplus land can be availed if efficiency of food production is improved. By applying more efficient agricultural production systems and optimising land allocation, future land requirements for food, feed and fibre production are reduced relative to growing population and thus some excess land can be used for growing energy crops. Lack of spatially explicit national data is major drawback in the analysis as use of global FAO/IIASA data leads to poor resolution at regional level.

Using scenarios analysis to 2015, Hoyt et al. [206] assessed first generation bioethanol and biodiesel production potential based on different levels of incremental land use and a set of assumptions (crops with high potential are assigned higher rate of expansion in the land area cultivated). The study also evaluates the entire biofuels value chain.

Using scenario analysis and GIS datasets, van der Hilst and Faaij [208] assessed the bioenergy potential from woody energy crops (including the corresponding cost of production) in Mozambique, while taking into account the developments in competing land use requirements. The study uses land availability results from van der Hilst et al. [60]. Competition for land and related effects of (i)LUC are not allowed in the study, and thus the land availability was modelled while taking into account the land required for other land use functions such as nature conservation and food production. Food and feed demand are modelled as functions of population size, GDP, food intake per capita and self-sufficiency provisions.

3.5.3. Improvements in agricultural and forestry management and technologies

In both Batidzirai et al. [205] and van der Hilst and Faaij [208], the efficiency of the agricultural sector is a key factor for the land required to meet the total demand for food, animal products and bio-materials. According to Batidzirai et al. [205], up to 45 Mha of the country's agricultural land could (in theory) be made available for bioenergy crop production in Mozambique by 2015, but under the condition that there is rapid advancement of agricultural technology and animal production systems and thereby an increment of efficiency of production.[11] In van der Hilst and Faaij [208], a scenario approach was used to explore potential long term developments in the productivity of the agricultural sector. One scenario projects future yields based on historical performance while a more progressive scenario assumes high efficiency in agricultural productivity and consequently more surplus land is made available for other purposes, including energy crop cultivation.

In their estimation of land availability for energy crops, Hoyt et al. [206] also employ high and low scenarios for both yields and costs. These scenarios reflect the use of varying levels of efficiency of agricultural production systems and agricultural technologies compared to current subsistence-type cultivation.

3.5.4. Use of marginal and degraded land

Land available for bioenergy production is classified into five productivity classes in van der Hilst and Faaij [208] and in Batidzirai et al. [205]. In van der Hilst and Faaij [208], the productivity classes provide the percentage of the maximum attainable yield given the level of agricultural management. For example, the non-productive category includes areas that produce $<20\%$ of the maximum attainable yield while the productivity of marginally suitable soils is 20–40%. In Batidzirai et al. [205], land is classified into very suitable to marginally suitable categories depending on productivity.

Hoyt et al. [206] assume that the total available area for agricultural expansion is about 10.5–13.2 Mha.[12] About 9 Mha of arable land is considered extremely constrained for conventional agricultural due to conditions of topography, climate, hydrology and soil structure conditions. But this area could potentially be used for bioenergy feedstock production. Due to lack of good quality land statistics of the country, these land estimates were based on simple calculations. A report by Matavel and Ribeiro [209]—which is not a resource assessment study, but evaluates the socio-economic impacts of biofuels production in Mozambique—estimates that about 40 Mha of marginal land[13] are potentially available for biofuels feedstock development in the country.

3.5.5. Water availability and use

Water availability is implicitly included in Batidzirai et al. [205] and Hoyt et al. [206] as land suitability generally reflects both agro-ecological conditions as well as the availability of water

[11] Model results from study indicate that current average crop yields could increase by 4.9–8.9 times. But this has not happened since 2005 when the analysis was conducted.

[12] According to Hoyt et al. [206], only 27 of the 36 Mha of arable land are actually cultivable; 5–8 Mha are currently cultivated, human settlements could require 13–16 Mha.

[13] This figure is generally quoted by the Government of Mozambique officials e.g. the Mozambican Minister of Energy's presentation at the First International Energy Week Seminar, Santo Domingo, Dominican Republic, 17th January, 2008.

Table 7
Summary of land and biomass energy potential in five selected countries.

Biomass category[a]	United States		China		India		Indonesia		Mozambique	
	Low	High	Low	High	Low	High	Low	High	Low	High
Land resources (Mha)										
Marginal/degraded land	7.1	11.2	6.7	126	14	64	12	74	9	40
Surplus agricultural land	0.04	16.2		54		26	0	34	0	45
Other lands				12.3	3	65				
Total land	**7.16**	**27.4**	**6.7**	**192.3**	**17**	**155**	**12**	**108**	**9**	**85**
Agricultural Biomass (land dependent)										
Perennial crops on surplus agricultural land (PJ)										
● woody crops	3120	7180	3600	6380	521	2604	726	1234	1,378	5,373
● grasses	–	–	–	–	–	1,680	–	–	–	–
Perennial crops on marginal land (PJ)										
● woody crops/grasses	360	1,680	48	4,536	–	3,420	282	2,087	119	1,327
Subtotal perennial lignocellulosic feedstocks	**3480**	**8860**	**3648**	**10,916**	**521**	**7704**	**1008**	**3321**	**1,497**	**6,700**
Other first generation biomass resources (PJ)										
Oil crops on surplus agricultural land	–	–	–	–	–	936	–	–	–	–
Oil crops on marginal/degraded land	–	–	–	42	1.2	14	5,1	35	13	98
Grains and sugar crops:										
● sugarcane	–	–	–	–	5.0	562	13	69	7.5	
● maize (corn), cassava, sweet sorghum	147	776	130	640	–	–	–	–	–	–
● soy	1.5	59	–	–	–	–	–	–	–	–
Subtotal first generation crops	**149**	**835**	**130**	**681**	**6**	**1512**	**18**	**104**	**21**	**161**
Residues (land independent and current data)										
Forest Biomass (PJ)										
Forestry industry processing residues										
● primary mill residues	32	480	54	576	–	62	26	59	–	1.9
● secondary mill residues	52	440	120	520	–	138	–	30	–	–
Logging and site-clearing residues	1132	1280	800	6113	–	–	75	223	–	0.9
Forest thinning/fuel treatments	–	1,200	–	–	–	–	820	5360	–	17
Fuelwood extraction/sustainable harvest	–	320	–	580	–	1500	–	–	–	–
Urban wood residues	618	780	–	–	–	–	–	–	–	–
Subtotal forestry residues	**2283**	**4052**	**974**	**7789**	–	**1700**	**921**	**5672**	–	**20**
Agricultural residues (land independent) PJ										
Annual crop residues										
● crop residues	1695	6690	419	3600	102	6565	15	1476	123	159
● wasted grain	–	–	–	–	–	94	–	20	–	–
Miscellaneous residues										
● food processing residues,	1680	1740	–	2000	–	183	–	–	–	–
● livestock manure	33	660	–	2095	86	219	1	290	–	–
● MSW, landfill gas	–	640	–	200	336	844	–	48	–	–
Subtotal agricultural residues	**3408**	**9730**	**419**	**7895**	**524**	**7905**	**16**	**1834**	**123**	**159**
TOTAL	**9319**	**23,476**	**5171**	**27,280**	**1051**	**18,822**	**1963**	**10,931**	**1,641**	**7,039**

Remark: All values are in Petajoules (10^{15} J) Higher Heating Value. Biomass amounts are in dry tonnes.

[a] Potential estimates of land resource availability and land dependent biomass resources are projected for the period up to 2030. Biomass potential from land independent resources such as residues is based on current socio-economic and biophysical conditions and represent current biomass resource availability. Unless specifically mentioned, all biomass estimates represent technical potentials, i.e. it is assumed that demand for land for food, feed, fibre and other competing applications such as biomaterials, and infrastructure is fulfilled first before resources are allocated for bioenergy applications. It is also assumed land conversion for biomass excludes forested areas and other protected areas.

resources. Van der Hilst and Faaij [208] uses a more spatially explicit modelling whereby the relative crop yields are a function of climate and soil conditions on a spatial resolution of 5 Arc-minutes. However, it does not consider the water availability at a watershed level and thus potential scarcity and competition is not included.

3.5.6. Nature protection and expansion of protected areas and climate change

The reviewed studies have taken into account basic sustainability issues, such as minimising food–fuel conflicts and nature protection, but many other issues remain unaccounted. Van der Hilst and Faaij [208] excluded protected areas, forested areas and land with steep slopes ($>16\%$) from conversion to energy plantations. In Batidzirai et al. [205] and Hoyt et al. [206], protected areas and forested areas are also excluded from land availability calculations. All the studies do not include the impacts of climate change on future biomass availability. However, Batidzirai et al. [205], analyses bioenergy supply chain with the least carbon footprint.

3.5.7. Use of agricultural and forestry by-products

The potential of agricultural crop residues from Mozambique has not been estimated. Batidzirai et al. [205] argues that there is limited economic biomass potential from agricultural harvesting and processing residues because of the dispersed and peasant nature of agricultural activities, without quantifying the crop residue resource. However, van Dam et al. [210] asserts that 40% of sugarcane leaves and tops waste stream can be recovered and used for energy. Due to lack of data, no study has attempted to estimate secondary and tertiary agricultural residues in Mozambique.

3.5.8. Cost of biomass production

Although the three main national studies have analysed the biomass production costs for different types of crops as well as supply chain logistic costs, there are some weak spots in the cost of supply information. For example, Batidzirai et al. [205] use average productivities for each agro-ecological zones and thereby ignore spatial variation in productivity in the various regions. This is however, included in Van der Hilst and Faaij [208], where spatially explicit productivity and logistic data is used in the economic analysis. None of the studies include the impacts of bioenergy production on agricultural and energy markets.

4. Summary of harmonised biomass energy potentials in the five selected countries

We summarise below, the synthesised biomass energy potentials in each of the five countries. A summary of the potentials is also shown in Table 7.

4.1. Biomass energy potential in the USA

Total technical biomass potential in the US (after satisfying food, feed, and fibre requirements) from the agricultural and forestry resources is estimated to be between 9.3 and 23.5 EJ. About 80% of the biomass resource potential is from agricultural lands (7–19.4 EJ) and remaining 20% is from forestry resources (2.3–4.1 EJ). Perennial crops[14] such as switchgrass grown on surplus agricultural land and on marginal land contributes about 38% to the total potential. Agricultural crop residues are also an important biomass resource contributing about 40% to the national potential. As shown in Table 7 first generation biofuels[15] are expected to play a marginal role in future bioenergy systems.

Differences in the estimates of bioenergy potentials arose because the studies used different base year data sets, different sustainability assumptions, considered different resources and competing biomass applications. For forest resources, Milbrandt [180] used the USDA Forest Service's Timber Product Output database for 2002 as a basis while Perlack et al. [11] used much more extensive data sources ranging from the 1997 US land inventory to the Agriculture Biomass Feedstock Supply survey of 2003. Milbrandt [180] does not consider biomass from forest thinning/fuel treatments, or sustainable fuelwood extraction. With regards to agricultural residues, the studies used different residue removal thresholds. Perlack et al. [11] assume no-tillage scenarios that allow removal of greater amounts of residues together with improvement in collecting technology while Milbrandt [180] assumes that 35% of the residues could be collected as biomass. Bioenergy potential from energy crops differ because Milbrandt [180] considers only crops grown on CRP lands and abandoned mineland and uses an average yield of unirrigated switchgrass, willow and hybrid poplar; while Perlack et al. [11] assume active cropland, idle cropland and cropland used as pastures can be used for bioenergy production.

4.2. Biomass energy potential in China

China is a large country with enormous land resources. But it also has a large population and many competing land uses, which diminish the total potential for biomass production. About 54.6 Mha of reserved arable lands have been identified as potential land for biomass production. Xinjiang Province represents about half of the total reserved arable land potential. In addition, about 126 Mha of marginal/degraded lands suitable for forestry, are available for development of woody biomass crop plantations. Estimated biomass energy potentials range from 5.2 to 27.3 EJ/yr. Perennial woody biomass[16] is expected to contribute between 40 and 71% while agricultural residues[17] provide 8–29% of the total bioenergy. Forestry based biomass[18] provides 21% of total bioenergy potentials.

For China, main differences in bioenergy potentials are due to use of different assumptions e.g. on crop yields and sustainability demands, data sets, differences in types and amounts of lands used for bioenergy production. While Kline et al. [159] use international databases and estimate "available equivalent arable land" from FAO Terrastat and FAOSTAT, other studies such as Sun [181] use national land use statistics and explore possibilities for using marginal land for bioenergy production. Sun [181] is also explicit in the land types that are excluded e.g. sensitive ecosystems. In terms of energy crop yields, Kline et al. [159] assumed average biomass productivity of 2.24 tdm ha^{-1} yr^{-1}. Sun [181] on the other hand considers varying scenarios with different biomass

[14] This includes woody biomass on 14.16 Mha with productivities of 11–18 td Mha^{-1}. Woody crops for fibre are assumed to be cultivated on an additional 2 Mha (average yields 13–18 tdm ha^{-1}) of which 25% is used for bioenergy. About 10% of biomass is assumed lost in harvest operations.

[15] Up to 75 Mt of corn can be used for bioethanol production under different scenarios. 2.6–7.9 Mt of soybeans can be used for biodiesel production. It is assumed that the US also fulfils its domestic and international grain supply obligations.

[16] Switchgrass potential cultivated on 54.6 Mha of the reserved lands under different scenarios is about 6.4 $EJyr^{-1}$.

[17] Crop residues in China are dominated by corn stover; soybean residues are excluded, only 33% of corn stover and 14% of wheat residue are available for sustainable recovery.

[18] Only 14% of forestry residues are being utilised mainly for industrial materials e.g. fibreboard and fuelwood. The remaining 86% could be utilized as biofuel feedstock.

productivities depending on land quality, and also assumes switchgrass is cultivated on reserve lands while trees are grown on marginal lands.

The selected studies also employ different residue recovery factors. For instance, Kline et al. [159] assume only 33% of corn stover and 14% of wheat straw are available for sustainable recovery. Sun [181] on the other hand considers crop residues from all agricultural crops grown over 122 Mha and uses a crop harvest index, a residue recovery rate and takes into account competing residue applications. CAREI [182] assumes different harvest index values when deriving potential residues. Similar differences are also found with regards to forestry resources.

4.3. Biomass energy potential in India

Biomass energy potential in India is dominated by agricultural resources. Wastelands represent the most important resource and the government is targeting these marginal lands for developing mainly first generation tree borne oil seed crops. India has potential to produce between 1.05 and 18.8 EJ of biomass energy from forestry and agricultural feedstocks. There is a limited biomass potential from forestry resources, as most of the 1.7 EJ estimated is supposed to come from fuelwood substitution. Agricultural resources comprise of 7.7 EJ of mainly lignocellulosic biomass from dedicated perennials trees and grasses (40–50% of total). There is also potential of 1.5 EJ from first generation oil seed crops such as Jatropha as well as grains and sugar crops. Furthermore, agricultural residues can provide another source of biomass feedstocks, with 6.5 EJ of conventional crop residues[19] and 844 PJ of MSW, waste water and landfill gas.

Assessments of bioenergy potential from energy crops in India differ because of the different land availability estimates used in the various studies. TERI [188] identify at least six categories of land categories totalling 13.4 Mha which could be used for energy crops, including fallow lands and mixed cropping systems. IRG [189] argues that there are about 14.2 Mha of new, currently "underutilised" lands that could be used for energy crops. Sudha and Ravindranath [190] estimate that between 43 and 130 Mha could potentially be available for biomass production including 26 Mha of surplus cultivable land. However, according to Kline et al. [159] there is no surplus agricultural land in India as all the 170 Mha of total land arable available which can be classified as "equivalent suitable for cultivation"[20] is cultivated or in permanent crops.

Land use modelling by Schaldach et al. [193] show that any expansion in biofuel feedstock production in India is likely to result in pressure on land resources, even if agricultural productivity improves significantly. Thus wastelands are a considered major resource for energy crop cultivation. However, there are different estimates of the extent of wastelands in India, mainly due to differing definitions of wastelands used by various agencies. For example, the amount of wastelands that can be used for growing of biomass is estimated in Ravindranath and Balachandra [191] to be 35 Mha, while in Rajagopal [194], it is only 17 Mha.

Differences in residue generation and availability for energy are mainly due to use of different base year values for agricultural production and amounts devoted to competing applications. For instance, Ravindranath and Balachandra [191] estimate that about 450 Mt of surplus agricultural crop residues are available using 2003 agricultural production data, while available residues according to Ravindranath et al. [192] amount to 325 Mt (based on 1996–97 agricultural production data).

4.4. Biomass energy potential in Indonesia

Indonesia has over 16 Mha of surplus agricultural land that could be used for growing energy crops.[21] In addition, there are an estimated 12–74 Mha of degraded land which could potentially be available for biomass crop cultivation. Biomass technical potential in Indonesia is estimated to be between 1.0 and 3.3 EJ of lignocellulosic energy crops (30–50%), in addition to first generation crops such as oil palm, etc. Overall, bioenergy technical potentials range from 2.0 to 10.9 EJ. Key biomass energy resources include rice residues with a technical energy potential of 150 PJ, rubber wood (120 PJ), sugar residues (78 PJ), palm oil residues (67 PJ), and about 20 PJ/yr from plywood and veneer residues, logging residues, sawn timber residues, coconut residues, and other agricultural wastes. In addition, there is potential to utilise sustainable forest harvest of up to 5.2 EJ.

Wicke et al. [92] and IRG [189] are the only studies that estimate surplus agricultural land which can be used for energy crops, the former based on palm oil productivity scenarios and the latter on so-called underutilised lands. Most bioenergy assessments target degraded lands for energy crop production, given the scarcity and sensitivity of cropland in Indonesia discussed earlier. However, there are widely varying estimates of available degraded land in Indonesia. An illustration of how much degraded land estimations vary is given by Wicke et al. [203] quoting various references: the Ministry of Forestry (74 Mha), FAO (31 Mha), WWF (18 Mha), and CIFOR (12 Mha). This variance in degraded land estimations is mainly the result of different methods and definitions used to identify degraded land. It is also attributed to issues related to policy and the increasing complexity of the direct and indirect causes of degradation [204].

Differences observed for studies that estimate agricultural residues emanate from using different base year crop production figures and different assumptions about amounts of residues used in competing applications. For example, Kamarrudin [200] uses 1998 crop production data, Panaka [211] uses 2003 data while Duryea [199] uses 2004 production data. Similar differences also apply to forestry residues.

4.5. Biomass energy potential in Mozambique

Total biomass energy potential in Mozambique is estimated to be between 1.6 and 7.03 EJ. The country has capacity to produce up to 6.7 EJ of bioenergy annually from perennial energy crops[22] with moderate introduction of agricultural technology under strict sustainability criteria. Essential for realising this potential is rationalisation in agriculture and livestock raising, and potential increases of up to seven times current productivities can be achieved with moderate technology introduction. In the short term, up to 45 Mha of surplus agricultural land can be availed for other purposes including energy crop growing. Other estimates put agricultural land availability at between 10 and 19 Mha. Marginal land is estimated at 9 Mha and could be useful for growing woody

[19] Use of crop residues depends on their calorific values, lignin content, density, palatability and nutritive value. Residues are mainly used as fodder for cattle, fuel for cooking and thatch material for housing. Rice and wheat straws have the highest potential. Currently 50% is burnt in the fields.

[20] Kline et al. [159] use data sets from FAO "TerraStat". The "available equivalent arable land" is defined and based on the total potential (from TerraStat) less the land reported as in use in FAOStat, i.e. Total land available "equivalent suitable for cultivation"—(Cultivated arable land + land under permanent crops) = available equivalent arable land.

[21] From 16.67 Mha of currently "underutilized" lands, 2.94 billion litres of ethanol from sugarcane and 990 million litres of biodiesel from jatropha can be produced assuming high yields.

[22] Using eucalyptus with productivities of between 7 and 25 tdm ha^{-1} yr^{-1} (for arid to productive regions).

biomass. Potential biomass from forest logging residues is estimated to be about 850 TJ while 1.9 PJ of biomass is potentially available from waste in timber processing industries, giving a combined residue potential of about 2.7 PJ.

There are only a few bioenergy assessments conducted for Mozambique, and these studies focus on different bioenergy resources, and also use different timeframes. While Batidzirai et al. [205] and van der Hilst and Faaij [208] explore the potential of woody perennials in 2015 and 2030 respectively, Hoyt et al. [206] focus on short term potential of first generation crops. Other differences that arise are due to use of different methodologies; Batidzirai et al. [205] and Hoyt et al. [206] use bottom up statistical analysis while van der Hilst and Faaij [208] use spatially explicit GIS analysis in the energy cropping production assessments.

4.6. Synthesis

We summarise below key observations from the review exercise. As a general conclusion, none of the selected studies covered all the basic elements expected in an ideal bioenergy assessment. Except for the US 'billion ton' studies, none of the studies attempt to address all key potential biomass resources, and most of the studies focus on first generation technologies. The studies are largely based on statistical analysis, and only a few studies apply spatially explicit analysis and advanced GIS modelling. Similarly, cost of biomass production and economic analysis are generally limited, and only a handful of studies develop bioenergy cost supply curves. Also, every assessment attests to incorporating some basic sustainability criteria such as avoiding future food fuel conflicts and excluding protected areas, but there are marked differences in the level of parametric detail and methodological transparency between studies. Also, except for USDoE [32], no integrated assessment is performed for any of the selected studies, to evaluate e.g. macro-economic feedbacks.

Compared to other countries, studies conducted for the US are more comprehensive, use state of the art analysis and the methodology and assumptions used are more explicitly discussed. Furthermore, availability of detailed country specific data and historical trends enable better modelling of biomass potentials. For the other selected countries, not all potential biomass resources available in the country are explored and most studies focus on first generation crops, e.g. oil palm, jatropha and sugarcane. For Indonesia, the potential of perennials has not been assessed.

Competition between biomass for energy and other competing applications such as food, feed and biomaterials is crudely analysed in most studies and key assumptions used such as population projections, income, food demand, crop productivities, land quality and agricultural management are not explicitly discussed. Also, human diets and possible protein chains are hardly included, while the impacts of different animal production systems are not assessed in detail.

Some of the studies do take into account expected learning in agricultural and forestry production systems (including breeding and impacts of no-tillage systems) on biomass potentials, but the underlying assumptions such as yields, efficiencies and costs are not explicitly discussed.

The quality of land availability analysis varies greatly from crude national average values to more spatially explicit evaluations that provide more localised detail. In addition, the use of marginal and degraded land is included in several studies, although due to lack of spatial detail, most of the selected studies use average crop productivities that do not take severity of physical constraints into account. The reviewed studies also lack clarity on the current use of marginal lands, their biodiversity content as well as national policies on their use. Generally, statistics on marginal and degraded land vary widely due to poor mapping and datasets.

A few studies discuss water availability as a constraint and only those assessments that give detailed spatial resolution consider localised climate conditions including soil–water conditions. Most studies use average biomass productivities based on rain-fed conditions and ecological zoning. Competition for water resources is hardly taken into account in the selected studies, as this requires additional water balance analysis at the watershed level. In addition, none of the studies consider climate change impacts on biomass potential or vice versa, although reference is made to the need for carbon sequestration as well as minimisation of carbon footprint of bioenergy production pathways.

Nature protection is included in all the studies, although this is limited to exclusion of protected and forested areas. The possibility of expansion in protected areas is however, hardly taken into account. The restrictions on residue removal that are included in some studies are linked more to the need to maintain soil quality than to efforts to maintain biodiversity. Only van der Hilst and Faaij [208] include the effects of (i)LUC and but none of the studies include the effects of (avoided) climate change.

5. Recommendations for a comprehensive bioenergy resource assessment analytical framework

Based on lessons learnt from the review of state of the art biomass energy resource assessments and methodological insights discussed in Section 2, we propose here an analytical framework for evaluating sustainable biomass energy potential that takes into account key drivers and factors that influence the available biomass resource potential. The starting point of such an analytical framework is the definition of a set of ecological and socio-economic sustainability criteria[23] that define the constraints under which the biomass resource can be sustainably secured. These sustainability criteria should ideally be based on internationally standardised criteria, but additional country specific requirements and conditions may also be important to take into account. See van Dam et al. [212] for more details on sustainability criteria. Such criteria are directly linked to the key factors that determine the availability of biomass resources.

Assessing the sustainable biomass energy resource potential entails at least the six interlinked key stages shown in Fig. 6. This includes estimating the biomass energy technical potential, evaluating the cost of biomass production, identifying the economic biomass potential, and by taking into account the macro-economic and environmental impacts of biomass production, derive biomass energy resource potential that incorporates all dimensions of sustainability. In each step, the underlying assumptions and key parameters used in the calculations are made explicit while uncertainties are also revealed. Thus a fundamental requirement

[23] Typical ecological criteria include benchmarks for mitigation of greenhouse gas emissions and carbon stock changes, land use practices, biodiversity protection and appropriate agricultural management practices. Land use criteria aim to minimise indirect land use change and land use competition by reducing the conversion of natural forest to plantation while encouraging the use of degraded and marginal land. Biodiversity protection includes protection of high nature value areas, species habitats, sensitive ecosystems, and primary vegetation. It also involves control and monitoring of exotic species including issues of genetically modified organisms. Appropriate agro-management practices ensure biomass production is undertaken with minimal negative impacts on soil, water and air. Socio-economic criteria typically focus of promoting local development, ensuring fair labour and trade practices and respecting land use rights. For example, the local population should not suffer any disadvantages, and should benefit from the opportunities of biomass production. In addition, benchmarks for internationally recognized standards for working conditions must be respected [212,214,215].

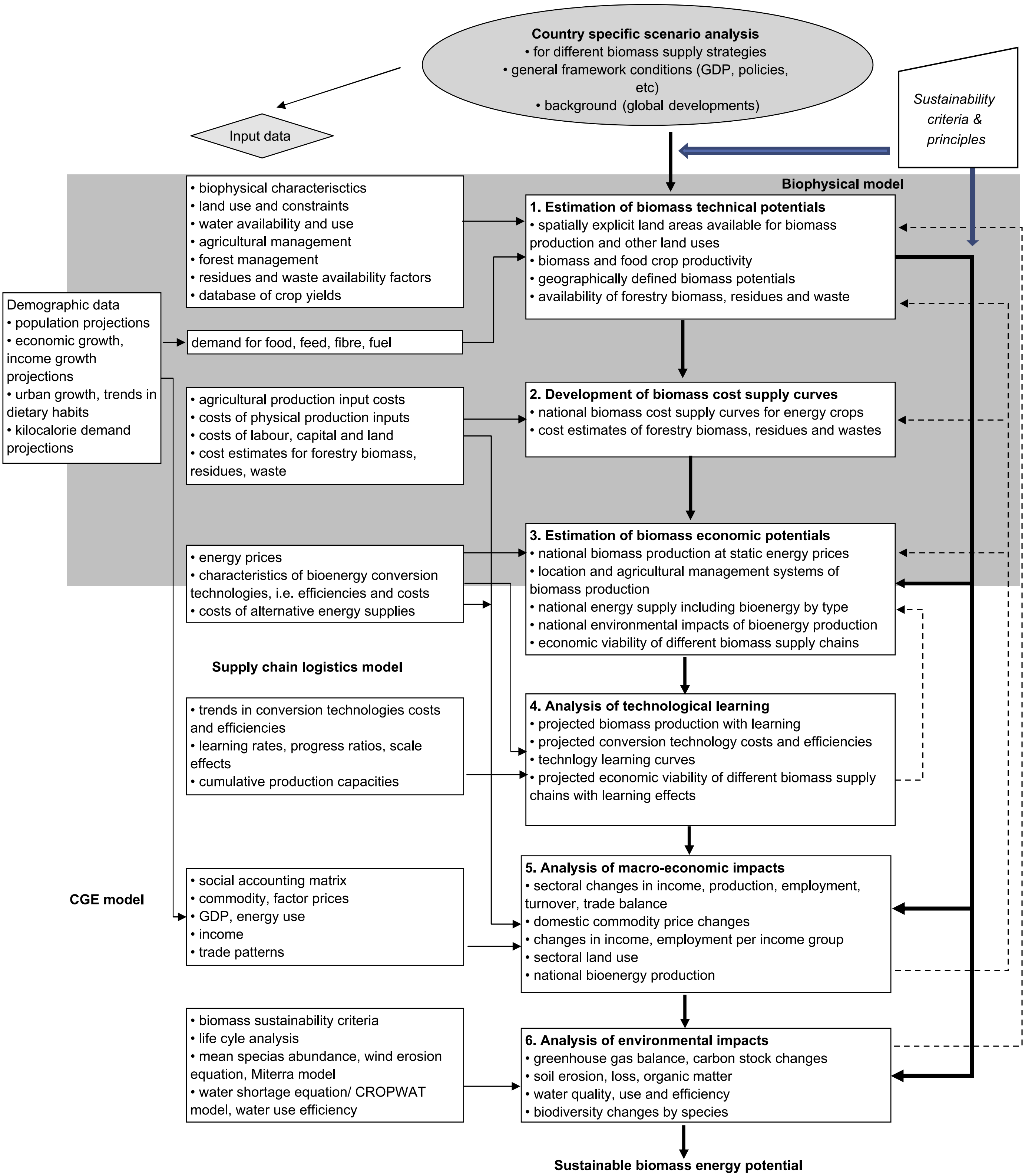


Fig. 6. Analytical framework for evaluating sustainable biomass production potential.

at each stage of the potential assessment is transparency, in terms of scope, methodology and datasets.

The first stage of the analysis involves estimating the technical biomass energy potential that is feasible to produce from available land in each setting based on various levels of efficiency of food and feed production while taking into account biophysical conditions that determine productivity (i.e. soil, water, climate). Similarly, the technical biomass potential from residues and wastes is based on the technical potential to collect agricultural and forestry residues and wastes while accounting for competing applications.

In the second step, the production costs of biomass feedstocks are evaluated taking into account relevant factors of feedstock production (labour, capital, land, fuel, machinery, fertiliser, etc.). Crop production costs strongly depend on land quality, yields and agricultural management as assumed in step 1 and are estimated based on the existing economic and technological conditions (as well as expected technological learning if applicable—this is included in step 4). As production conditions vary considerably by location and for different feedstocks, the production costs are expressed as cost–supply curves for different feedstocks. Also, since input costs are scenario dependent, several iterations are necessary to calculate the costs of inputs for various bioenergy production levels and for various other scenario assumptions.

The third stage involves the determination of the ‘economic biomass potentials’ or the amount of biomass that can be produced under a set of given economic criteria e.g. static food prices. The cost estimates are based on the biomass cost-supply curves from step 2, food prices, and supply chain logistics information. Given the diversity of biomass resources and conversion technologies, there are also many possible biomass supply chains and scenario variations. The economic performance of each component of the different bioenergy chains is evaluated and the economic viability of different biomass energy supply chains can then be assessed against the given economic criteria. This aspect is normally treated separately in economic potential analysis, with most studies providing only ‘farm gate’ cost analysis. Energy prices of alternative energy carriers can also be part of the scenario variations at this stage.

In the fourth step, technological learning (in feedstock production and conversion) and the subsequent cost reductions over time are taken into account in cost supply and economic viability calculations (i.e. step 2 and 3 respectively). The objective of this step is to establish endogenous relationships between cumulative production capacity and associated production cost reductions, and/or including scaling effects.

Step 5 evaluates the macro-economic impacts (e.g. changes in income, employment, pricing, food and energy prices, and the resulting feedbacks) of marginal increase in production of biomass. Country specific Computable General Equilibrium (CGE) models can be used for this analysis. The additional biomass production that is used as an input in the CGE model is based on the production cost structure and the type of biomass production derived from step 2 and 3 and/or the data for existing bioenergy supply chains that are already in the social account matrix.

The analysis in step 3 and 5 results in estimates of total biomass production that have to be consolidated. This is due to the fact that step 3 analyses the additional biomass production due to a comparison of supply costs and prices, while step 5 analyses the break-down of domestic impacts of biomass production. As a consequence iterations between economic potentials of biomass production from module 3 and production level in different sectors in step 5 are necessary. Several iterations are also required between step 5 and step 2, because the production of bioenergy can have several impacts on the costs of inputs (e.g. labour, capital, land, fuel, machinery, fertiliser, etc.), which are assumed constant in step 2.

The sixth stage evaluates the socio-economic and environmental impacts of large-scale bioenergy production. Its objective is to analyse the socio-economic and environmental performance of selected bioenergy chains on a regional level for a defined set of land use scenarios and also to get insight in possible consequences of sustainability principles for the potential of biomass energy and its economic performance. This is based on a set of defined principles with indicator based criteria. Several iterations are also necessary between step 6 and step 1 to step 3, as the additional stringent sustainability criteria impacts of the technical and economic biomass energy potentials. This final screening provides insights into the sustainable biomass energy potential and associated economic viability of different supply chains under different scenarios.

As shown in Fig. 6, some factors are important for determining the technical potential (e.g. biomass demand for food and materials which affects availability of appropriate land and water resources) while others are critical in evaluating the economic potential of bioenergy (e.g. agro-economic setting, applied agro-management systems and environmental impact requirements). For evaluating the ecologically sustainable bioenergy potential, environmental criteria such the carbon footprint, protection of biodiversity, water and soil need to be taken into account. Further, these factors are interlinked to and affect the different bioenergy potential types (including through feedback mechanisms).

5.1. Final remarks

Given the spatial heterogeneity of agro-ecological conditions in most countries and to satisfy the demands of detailed spatial land use modelling; there is critical need for high quality and detailed spatial data, especially high resolution land use mapping. Temporal land use change variations also need to be captured using historical trends to predict future land use dynamics and enable calibration of bioenergy assessment models. It is important to account for the temporal dimension, as the rate of development of bioenergy production leads to socio-economic and environmental impacts and feedbacks that need to be factored into future bioenergy potentials.

At best, bioenergy assessments need to employ harmonised approaches and transparent methodologies to cater for the diversity of methodologies, assumptions and datasets being employed in current assessments. Our analysis has shown that most current studies do not include all major factors and basic (sustainability) elements that are important determinants of bioenergy potentials.

While every assessment attests to incorporating some basic sustainability criteria such as avoiding future food–fuel conflicts and excluding protected areas, there are marked differences in the level of parametric detail and methodological transparency between the studies. Competition for biomass resources among the various applications is crudely analysed in most studies and key assumptions such as demographic dynamics, human diets and possible protein chains, biodiversity protection criteria, etc. are not explicitly discussed, while the impacts of different animal production systems are hardly included. In addition, land availability and suitability generally lack spatial detail and especially degraded and marginal lands, as well as pastures are poorly evaluated. The reviewed studies also lack clarity on the severity of physical constraints and current use of marginal lands, as well as their biodiversity content. A few studies discuss water availability and competition as a constraint and only those assessments that give detailed spatial resolution consider localised climate conditions including soil–water conditions. Some studies take into account improvements in management of agricultural and forestry production systems, but the underlying assumptions such as yields, efficiencies and costs are hardly discussed. Nature protection is included in most of the studies, although this is often limited to exclusion of protected and forested areas. Most of the studies are also methodologically incomplete as they do not incorporate important feedback effects that are an inevitable consequence of large scale bioenergy production. Direct and indirect land use change impacts, effects of (avoided) climate change and macro-economic impacts of large scale deployment of bioenergy are hardly taken into account.

The choice of approach and methodology for assessing bioenergy potentials depends on the type of expected results which in turn depend on the available data, timeframe and impacts. Thus, different methodologies need to be applied to estimate technical, economic, sustainable or implementation bioenergy potentials. While it is adequate to account for spatial constraints and environmental conditions in assessing technical bioenergy potentials, additional socio-economic and environmental criteria and targets are important considerations for sustainable bioenergy assessments. Economic potentials need to account for additional cost of bioenergy supply and other economic criteria, as well as macro-economic effects of large scale bioenergy production on food and energy markets. This is typically modelled using CGE models. When implementation potentials are considered, then the rate of bioenergy deployment as well as improvements in agricultural production systems are important considerations that need to be taken into account. Further, the level of spatial detail included in an assessment also depends on the geographical scope, from regional to global. At regional level, high resolution datasets are important especially for coherent environmental impact analysis. Global scale assessments typically use forward looking timeframes (e.g. 2050–2100) that incorporate important global scenarios and use more aggregated datasets.

The integrated assessment framework recommended in this study could ideally be applied to incorporate all the requisite elements, combining top down macro-economic analysis with bottom up biophysical modelling and including all important feedback effects.

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